ChainCluster: Engineering a Cooperative Content Distribution Framework for Highway Vehicular Communications

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***Abstract*—The recent advances in wireless communication techniques have made it possible for fast-moving vehicles to download data from the roadside communications infrastructure [e.g., IEEE 802.11b Access Point (AP)], namely, Drive-thru Internet. However, due to the high mobility, harsh, and intermittent wireless channels, the data download volume of individual vehicle per drive-thru is quite limited, as observed in real-world tests. This would severely restrict the service quality of upper layer applications, such as file download and video streaming. On addressing this issue, in this paper, we propose ChainCluster, a cooperative Drive-thru Internet scheme. ChainCluster selects appropriate vehicles to form a linear cluster on the highway. The cluster members then cooperatively download the same content file, with each member retrieving one portion of the file, from the roadside infrastructure. With cluster members consecutively driving through the roadside infrastructure, the download of a single vehicle is virtually extended to that of a tandem of vehicles, which accordingly enhances the probability of successful file download significantly. With a delicate linear cluster formation scheme proposed and applied, in this paper, we first develop an analytical framework to evaluate the data volume that can be downloaded using cooperative drive-thru. Using simulations, we then verify the performance of ChainCluster and show that our analysis can match the simulations well. Finally, we show that ChainCluster can outperform the typical studied clustering schemes and provide general guidance for cooperative content distribution in highway vehicular communications.**

***Index Terms*—Clustering, cooperative content distribution, Drive-thru Internet, highways.**

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I. Introduction

With Internet and vehicles now representing the two most prominent elements of our modern lives, providing in-vehicle Internet access to road travelers has become ever more important [1]. By deploying a multitude of wireless gateway points along the roadside, namely, roadside units (RSUs), the vehicles are possible to acquire temporary and opportunistic wireless connections to the Internet when driving through the coverage of RSUs, and accordingly enjoy limited Internet services. Such a fundamental vehicular communication framework is referred to as the Drive-thru Internet [2], [3].

Compared with the indoor wireless local area network (WLAN) scenarios, efficient communications in the Drive-thru Internet is a much more challenging task [4], which mainly attributes to the following features of vehicular communications. First, the wireless connectivity from vehicles to RSUs is transitory due to the high vehicle mobility. As reported in [2], the overall connectivity range of an RSU is around 500–600 m, which allows a connection time of 15–18 s to a vehicle moving at the velocity of 120 km/h. In reality, the number of RSUs deployed along the road cannot be enough for providing the ubiquitous coverage due to the high deployment and maintenance cost, particularly in a sparse populated region, e.g., highways. Thus, cooperative intervehicle communications are typically required accordingly as a supplement to extend the RSU's coverage. Although the cellular networks can also be used to provide mobile network access for vehicles, which is completed coverage. However, the cellular communications are operated on the licensed spectrum, which will be prohibitively costly for transferring bulk data, e.g., video streaming. The RSUs have the advantage of low capital cost, easy deployment, and high bandwidth. Moreover, the RSUs can provide a potential way to offload the cellular networks [5]. Second, the Drive-thru Internet tends typically large-scale with a multitude of vehicles sharing (or contending) the channel simultaneously. For example, as indicated in [6], a stable highway traffic flow typically constitutes 20–30 vehicles per mile per lane. In other words, in an eight-lane bidirectional highway section with smooth traffic flow and a vehicle-to-vehicle (V2V) communication range to be around 300 m, approximately 30–45 vehicles will share the channel for transmissions at the same time. Ott and Kutscher [2] report a real-world measurement of the Drive-thru Internet on a highway road section. With a single vehicle connecting to a roadside IEEE 802.11b AP, a volume of 9-MB data per drive-thru can be acquired using either Transmission Control Protocol or User Datagram Protocol at a vehicle velocity of 80 km/h. This allows the download of a medium-sized file, such as an MP3 file. However, when a multitude of vehicles share the RSU for the transmissions synchronously, the individual throughput performance would degrade significantly due to the transmission contentions and collisions and can hardly afford the upper layer applications [7]. Therefore, a practical cooperative mechanism is highly demanded to convert vehicles from channel competitors to collaborators and to enhance the welfare of all vehicles.

As motivated by the aforementioned issues, in this paper, we develop a cooperative Drive-thru Internet framework for large-volume data distribution to vehicles in the highway environment. Specifically, note that, in the highway scenario, vehicles typically move along a linear topology and drive through the RSU consecutively. Thus, we propose to form vehicles into a chain cluster, so that the cluster members would drive through the RSU consecutively in a sequential order. Each cluster member is responsible to download a nonoverlapping part of file, and accordingly with all cluster members moving out the coverage of RSU, an entire file can be downloaded by cluster members but is divided into several parts and separately stored in cluster members. The cluster members then merge the downloaded file to the cluster head. To summarize, ChainCluster virtually extends the connection time of one vehicle to the collective connection time of a group of vehicles and therefore enhances the likelihood of intact file download during the short-lived connection time. Moreover, ChainCluster explicitly separates the download phase from RSU from the file merge and recovery phase when the entire cluster leave the RSU coverage. This can fully utilize the precious connection time of vehicles to RSUs. Within the ChainCluster framework, we develop an accurate and simple analytical framework to evaluate the data volume that could be downloaded for each cluster per drive-thru. In particular, our model investigates on the instantaneous download performance of vehicles by deploying a microscopic vehicular mobility model, as introduced in [8]. With the fundamental IEEE 802.11B Medium Access Control (MAC) applied, we derive the expression of the overall file download time.

The major contributions of this paper are threefold.

- Cooperation cluster in linear topology: Existing works largely group vehicles in a cluster where vehicles are mutually connected [9]–[11]. In contrast, we form cluster vehicles in a linear chain topology. The linear cluster is not only stable and allows reliable cooperation's among cluster members, but also effective to extend the connection time of a single vehicle to that of multiple vehicles, and therefore boosts the download performance.
- Fine-grain mobility model: Existing literature largely adopts the macroscopic mobility [12], [13], which considers vehicles as traffic flows and typically evaluates the averaged performance. Such a method is not accurate enough to evaluate the download performance of a single content file in a specific drive-thru scenario with given neighboring vehicles and velocity. To address this issue, we apply the microscopic mobility model, which captures the mobility features of a vehicle on highways to provide more accurate evaluation.
- Theoretical analysis and performance evaluation: We analyze the collective download performance of vehicles in the linear cooperation cluster on highways. Specifically, we first derive the MAC throughput performance of vehicles with specific mobility features during the drive through of RSU. We then evaluate the integrated data volume that can be cooperatively downloaded by the linear cluster. Finally, we analyze the download forwarding time to retrieve the whole content in the chain cluster. The proposed approach can provide a systematic solution for the adaptive control of upper layer media applications in highway vehicular ad hoc networks (VANETs), such as video streaming.

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 detailed scheme design for cooperative content distribution. Section V validates the accuracy of the analysis with simulations, and Section VI closes the paper with conclusions.

II. Related Work

Cooperative vehicular communications represent an effective approach to extend the RSU's coverage and have attracted an extensive research attention in the past. Various cooperative schemes have been proposed in VANETs accordingly, which can be usually divided into two categories [14], i.e., vehicle-to-RSU (V2R) and V2V communications. Our work combines both paradigms together to form a systematic solution for the highway scenario.

For cooperative download of large-sized content from roadside infrastructure in V2R communications, Trullols-Cruces *et al.* [15] consider an urban/suburban scenario, unlike the highway scenario, where it is hard to predict the contacts between cars. Trullols-Cruces *et al.* [15] devise the solutions for selecting the right vehicles to carry data chunks and assigning the data chunks among the selected vehicles. To improve the diversity of information circulating in vehicular networks, Zhang and Yeo [16] propose a cooperative content distribution system to distribute contents to moving vehicles via APs' collaboration. Based on the vehicular contact patterns observed by APs, the shared content can be prefetched in the selected representative APs, and the vehicles can obtain the completed data from those selected APs. Saad *et al.* [17] investigates the cooperative strategy among the RSUs by applying a coalition formation game, which coordinates the classes of data to serve their responsible vehicles. In addition, Liang and Zhuang [18] investigate the utilization of roadside WLANs as a network infrastructure for data dissemination, where the network-level and packet-level cooperation are both exploited.

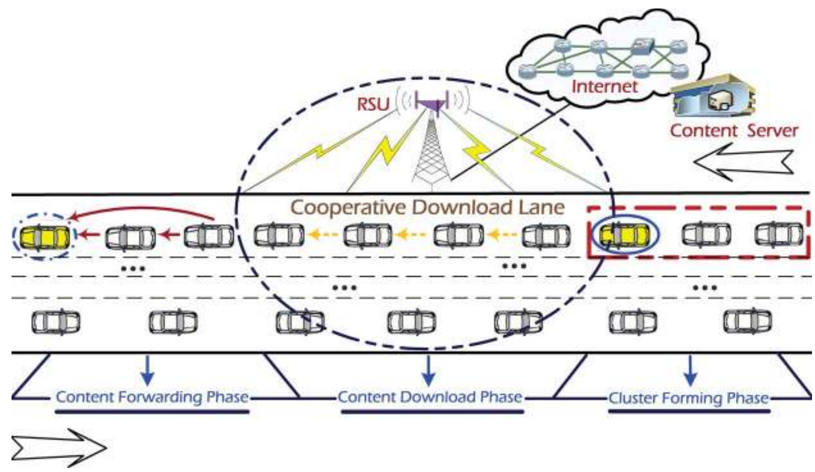

Fig. 1. Cooperative content distribution scenario for vehicles in highway Drive-thru Internet.

In terms of cooperative V2V communications, Nandan *et al.* [19] propose a swarming protocol and a piece-selection strategy to cooperatively exchange the pieces for the same content sharing among different vehicles. Sardari *et al.* [20] investigates a V2V collaboration scenario for distributing data to sparse vehicular networks, and by applying the rateless coding approach and using vehicles as data carriers, the reliable dissemination performance can be achieved. The authors in [21] address the V2V cooperation issue by introducing a delay-cooperative automatic repeat request (ARQ) mechanism and a vehicular route predictability-based carry-and-forward mechanism. To combat the lossy wireless transmissions and to achieve high-speed content sharing, the symbol-level network coding is adopted in V2V communications. Yan *et al.* [22] analyze the throughput of cooperative content distribution from RSUs. Due to the observation that the vehicles that are near to the AP have high signal strength, Zhao *et al.* [23] propose a relay-based solution to extend the service range of roadside APs. In addition, Li *et al.* [24] design a push-based popular content distribution scheme, where contents are actively broadcasted to vehicles from RSUs and further distributed cooperatively among vehicles. Wang *et al.* [25] discuss the maximum achievable amount of information that can be relayed forwarding along a vehicular stream. Brandner *et al.* [26] evaluate the packet delivery performance of low complex cooperative relaying by real-world tests. Wang *et al.* [27] introduce a coalitional graph game to model the cooperative vehicles for popular content distribution.

In addition, the high mobility, intermittent connectivity, and unreliability of the wireless channel can affect the cooperative performance of VANETs. To satisfy the need for massive data download and forwarding applications and to consider the aforementioned factors, the authors in both [28] and [29] investigate the cooperative MAC protocol in vehicular networks.

III. System Model

We consider a highway Drive-thru Internet, as shown in Fig. 1. An RSU is installed on the roadside, which serves as the gateway to provide Internet services to vehicles driving through its coverage. Throughout the work, we focus on a tagged vehicle, which subscribes to download a file from the RSU. The file size is considered to exceed the data volume that can be retrieved by the tagged vehicle itself per single drive-thru; otherwise, the problem is trivial. As such, a cooperation scheme is necessary. Furthermore, we define the low-speed driving lane as the cooperative download lane to avoid blocking up the free driving of followed vehicles.[1] With cooperation, the tagged vehicle and other cooperative vehicles can jointly conduct content download and distribution.

To help the tagged vehicle finish downloading the desired data volume, we form a vehicle cluster to cooperatively download the subscribed file for the tagged vehicle. The cluster appears a linear topology on the highways, and each cluster member is responsible to download and submit one separate part of the file to the tagged vehicle. With vehicles consecutively driving through the RSU, the cooperation scheme virtually extends the effective download time of the tagged vehicle to that of a long cluster. By adjusting the number of cluster members, the data volume that can be downloaded by the cluster for each drive-thru is thus controllable.

As shown in Fig. 1, the proposed cooperative scheme consists of three phases: cluster forming phase, content download phase, and content forwarding phase. Specifically, if the tagged vehicle would like to download a large-sized file, the tagged vehicle will invite other vehicles that followed itself to form a cluster. Once the tagged vehicle enters into the RSU's coverage, the tagged vehicle can evaluate the current saturated download throughput and select a target file. Several vehicles behind it are selected to form a linear cooperative chain cluster, which is called cluster forming phase. We assume the cluster forming time can be neglected for the reduction of tagged vehicle's download throughput. Within RSU's coverage, each vehicle in the cooperative cluster downloads one nonoverlapping part of the file sequentially from the RSU, which is content download phase. Outside the RSU's coverage, the tagged vehicle then collects the parts from the cluster members to recover the file and complete the final download procedure.

[1]Note that, as cluster members may be in different lanes, all of them can drive onto the download lane to form a linear chain cluster.

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbols Associated with Network Model	
$\nu_i(t)$	The velocity of vehicle i at time t.
$\eta_i(t)$	Random control parameter of vehicle i at time t for acceleration.
Ψ_{safe}, Ψ_{follow}	The safety distance and car following distance between two consecutive vehicles, respectively.
$d_{i,i+1}(t)$	The distance of two consecutive vehicle V_i and V_{i+1} at time t.
ζ	The coverage range by RSU.
Γ_i	Vehicle i's sojourn time within RSU's coverage.
Ω	The average received power in the fading envelop.
H	The set of K discrete modulation rates.
Symbols Associated with ChainCluster Scheme	
Λ	The set of M adaptive data-rate transmission zones.
ψ_k	The location of k-th zone within RSU's coverage.
N_{de}, N_{ar}	The set of departing vehicles and arrival vehicles, respectively.
T^{tag}	The set of individual running time point T^{tag} in the M zones.
$\tau_{k,i}$	The time point that vehicle V_i leaves the $k-th$ zone.
$\delta_i(\tau_k)$	The decision function to judge the changing state of CVN at τ_k.
$N_i^n(\tau_k)$	The CVN for the tagged vehicle V_i driving within n-th zone at time point τ_k.
Φ_{v_i}	The total data download volume by V_i within RSU's coverage.
Υ	The required data download volume.
N_c	The number of cooperative vehicles.
$\mathfrak{T}$	The average transmission probability of each vehicles in the linear chain.
$\mathbf{P}_{suc}$	The probability that one vehicle in the chain cluster transmits data on the channel successfully.
$\mathbf{Thr}$	The average MAC throughput from vehicle i to vehicle j in a cluster.
$E[X_{payload}]$	The average payload volume in the chain cluster transmitted successfully in a slot time.
$E[Y_{slot-time}]$	The average time slot length in DCF scheme.
$T_{\text{one-by-one}}$	Downloads forwarding time to retrieve a targeted file based on one-by-one forward strategy.
T_{best}	Downloads forwarding time to retrieve a targeted file based on best forward strategy.

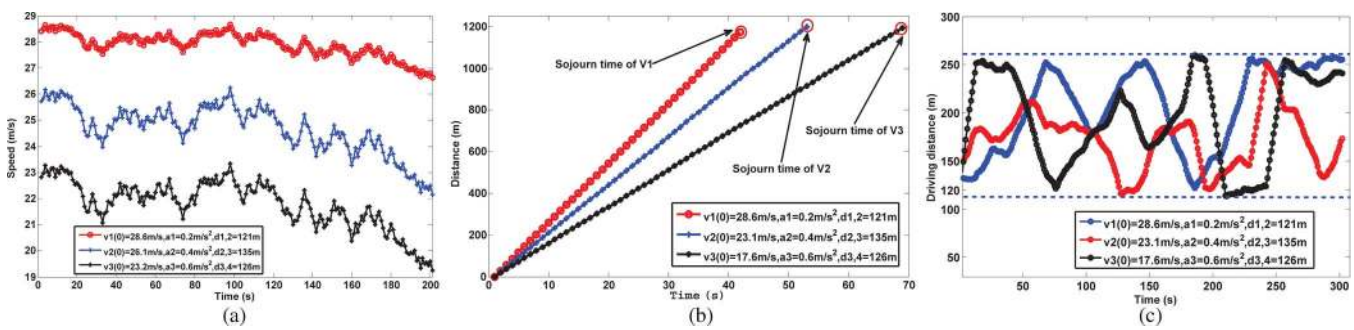

Fig. 2. Microscopic mobility tracking under different kinematic equation parameters. (a) Driving speed tracking. (b) Driving distance tracking. (c) Intervehicle distance tracking.

Due to the mobility of vehicles, the selection of cooperating vehicles and the performance of ChainCluster highly depends on the mobility features of vehicles and the throughput of their connections to the RSU and each other. In what follows, we introduce the vehicle mobility model and the throughput analysis of V2R and V2V communications. The many symbols used in this paper have been summarized in Table I.

A. Vehicular Mobility Model

We apply the kinematic equation with some real-world driving constraints to model the microscopic mobility behavior for the free driving of vehicles on highways, as shown in (1). The introduced microscopic vehicular mobility can be treated as a car-following model with corresponding speed and distance constraints, which are much closer to the real highway vehicular environment and widely used in the literatures [6], [8]. In particular, at the start of each time duration Δt, the vehicle updates its speed based on (1), then this vehicle keeps this updated speed during the whole period of Δt. That is

$$\nu_i(t+\Delta t) = \nu_i(t) + \eta_i(t) \cdot a \cdot \Delta t \tag{1}$$

where $\nu_i(t)$ denotes the velocity of vehicle i at time t, $\eta_i(t)$ denotes a random adjusting parameter for acceleration or deceleration at time t, a is a constant, and Δt is the updated time unit.

In addition, the vehicle mobility confines to two rules, namely, speed and distance constraints, as illustrated in Fig. 2.

– *Rule 1 (Speed constraint):* The velocity of each vehicle is restricted to the interval $[\nu_{\min}, \nu_{\max}]$, which represents the speed limitation on the road. In this manner, we track the vehicular velocity, denoted by ν_i, every Δt period. If $\nu_i(t+\Delta t) < \nu_{\min}$, then $\nu_i(t+\Delta t) = \nu_{\min}$; if $\nu_i(t+\Delta t) > \nu_{\max}$, then $\nu_i(t+\Delta t) = \nu_{\max}$. In this paper, we set $\nu_{\min} = 60$ km/h and $\nu_{\max} = 120$ km/h.
– *Rule 2 (Distance constraint):* The distance constraint between any two consecutive vehicles in the same lane includes: minimum intervehicle driving distance and maximal intervehicle driving distance. The former is referred to as safety distance, denoted by Ψ_{safe}, which depends on the vehicle's real-time velocity. The latter is an appropriate car-following distance, denoted by Ψ_{follow}, which can save more space for other driving vehicles. Let $d_{i,i+1}(t)$

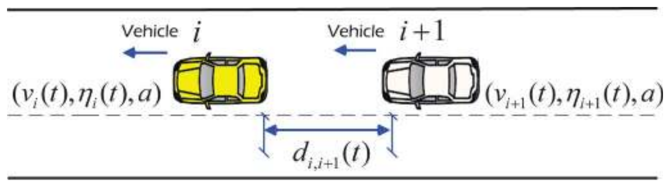

Fig. 3. Mobility model of vehicles on the highway.

denote the distance between two consecutive vehicles V_i and V_{i+1}. The constraint condition is regulated as follows: if $d_{i,i+1}(t) < \Psi_{\text{safe}}$, then $\nu_{i+1}(t) = \nu_i(t) - \theta \cdot a$; if $d_{i,i+1}(t) > \Psi_{\text{follow}}$, then $\nu_{i+1}(t) = \nu_i(t) + \theta \cdot a$. Typically, $0 < \theta \leq 1$, Ψ_{safe} is a constant that can be set between 50 and 120 m, and Ψ_{follow} is a constant that can be set to be less than 300 m.

We denote the initial intervehicle distances for all vehicles in the cluster by $d_{i,i+1}(t_0) = \Psi_{\text{safe}}(1 + \varepsilon_i)$, where ε_i is a random variable uniformly distributed in [0,1]. In the Drive-thru Internet scenario, the vehicle mobility intensely affects the sojourn time within RSU's coverage and data download volume. Therefore, we first investigate the tagged vehicle's sojourn time, and let Γ_i denote the sojourn time of vehicle V_i. Due to the driving speed and intervehicle distance restriction, the velocity of vehicles on the road are mutually dependent. For simplification, the tagged vehicle can be regarded as the head in a traffic queue. We provide extensive simulation results in Fig. 3 to numerically show the tracking results of vehicular speed, driving distance, and intervehicle distance with the proposed mobility model. In Fig. 3(c), we restrict the maximal vehicular interdistance to be under 260 m. Those results can be used to track the mobility states of individual vehicle in real time, which can be useful in the downlink analysis and Drive-thru Internet performance evaluation. According to (1) and the mobility rules, Γ_i is defined as follows:

$$\Gamma_i \triangleq \left\{ \tau_i \middle| \sum_{k=1}^{\left\lceil \frac{\tau_i}{\Delta t} \right\rceil} \nu_i(t_0 + \Delta t \cdot k) \cdot \Delta t = \zeta \right\} \tag{2}$$

$$\text{s.t.} \quad \nu_{\min} \leq \nu_i(t_0 + \Delta t \cdot k) \leq \nu_{\max} \tag{3}$$

$$\Psi_{\text{safe}} \leq d_{i,i+1}(t_0 + \Delta t \cdot k) \leq \Psi_{\text{follow}} \tag{4}$$

where $\nu_i(t_0) = \upsilon_0$, and t_0 is the initial time point that the vehicle V_i first enters the RSU's coverage range ζ. Usually, Δt can be set to as 1; (3) represents the max-min velocity restriction, and (4) represents the distance restriction; $d_{i,i+1}(t_0 + k \cdot \Delta t)$ can be calculated by

$$d_{i,i+1}(t_0 + \Delta t \cdot k) = d_{i,i+1}(t_0) + \sum_{q=1}^{k} \left(s_i(t_0 + \Delta t \cdot q) - s_{i+1}(t_0 + \Delta t \cdot q)\right) \tag{5}$$

where $s_i(t_0 + \Delta t \cdot q)$ is the driving distance of vehicle V_i at the $\Delta t \cdot q$th time interval, which can be denoted by $s_i(t_0 + \Delta t \cdot q) = \nu_i(t_0 + \Delta t \cdot q) \cdot (\Delta t)$.

B. V2R Communication Model

We consider an adaptive V2R transmission rate model [7], [12], in which the RSU's transmission rates depend on the distance from the RSU to the receiving vehicle. As shown in Fig. 4, the transmission rates received in those divided ranges are denoted by the rate set $C = \{c_1, c_2, \ldots, c_k, \ldots, c_M\}$, where c_k is the received data rate within the kth zone of RSU's coverage. The adaptive transmission rates within RSU's coverage are symmetrical, and $M = 7$ in the IEEE 802.11b standard. The transmission bit rates in different zones can be expressed as (6). For the ease of illustration, we consider an ideal MAC protocol similar to [12], in which the RSU airtime is equally allocated to vehicles in the coverage. Our work can also be easily extended to consider the more complicated MAC. That is

$$c_k(k = 1, \ldots, M) \triangleq \begin{cases} 1 \text{ Mb/s}, & k = 1{,}7 \\ 2 \text{ Mb/s}, & k = 2{,}6 \\ 5.5 \text{ Mb/s}, & k = 3{,}5 \\ 11 \text{ Mb/s}, & k = 4. \end{cases} \tag{6}$$

C. V2V Communication Model

It is necessary to have full knowledge of statistical properties of the V2V channel to analyze the communication performance [30]–[32]. Here, we adopt the real-world measurement results in [32], to analyze the physical layer capacity of V2V communications. For the typical short-distance connections feature, the distribution of received signal's amplitude in a vehicular receiver gradually transmits from Rician distribution to Rayleigh distribution as the intervehicle distance is increased. We model the fast-fading highway vehicular environment using the Nakagami-m distribution[2] [32], where the probability density function of signal amplitude can be represented by the Nakagami (μ, Ω) distribution as

$$\Im(x, \mu, \Omega) = \frac{2\mu^{\mu}}{\Gamma(\mu)\Omega^{\mu}} x^{2\mu - 1} \exp\left(\frac{-\mu}{\Omega} x^2\right) \tag{7}$$

where Ω is an average received power in the fading envelop and $\Omega = E(x^2)$; μ is a shape parameter related to the environment and the distance between the transmitting vehicle i and receiving vehicle j, denoted by $d_{i,j}$. According to the measurement result in [32] and the mobility model, if $90.5 \leq d_{i,j} \leq 230.7$, then $\mu = 0.74$; if $230.7 < d_{i,j} \leq 588.0$, then $\mu = 0.84$, and $\Gamma(\mu)$ can be represented as $\Gamma(\mu) = \int_0^{\infty} e^{-x} x^{\mu - 1} dx$, and Ω can be calculated as follows:

$$\Omega = \frac{\mathrm{P}_t G_t G_r h_t^2 h_r^2}{d_{i,j}^{\theta} L} = \varpi \cdot d_{i,j}^{-\theta} \tag{8}$$

where ϖ is a path loss parameter, $\varpi = (\mathrm{P}_t G_t G_r h_t^2 h_r^2)/L$, and θ is the path loss exponent.

With (7), we have the probability that the current signal-to-noise ratio (SNR) at the receiver is larger than a fixed threshold, as follows:

$$\Pr\left\{\frac{\Omega}{\lambda} > \wp\right\} = \frac{\Gamma\left(\mu, \frac{\mu}{\Omega}\lambda\wp\right)}{\Gamma(\mu)} \tag{9}$$

[2]This distribution is also widely used in V2V communication analysis and evaluation, e.g., [33].

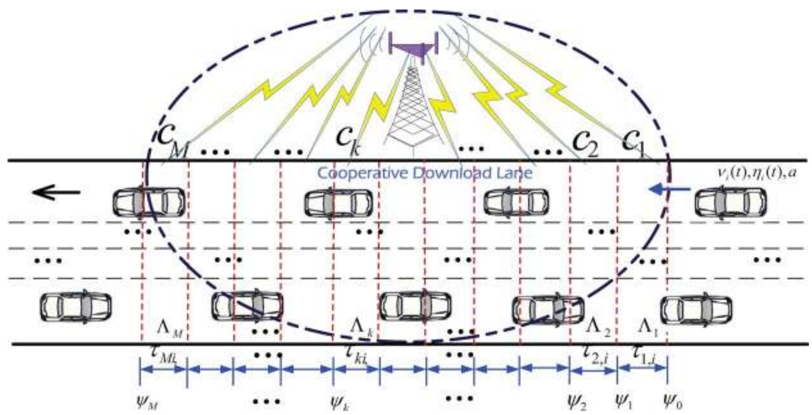

Fig. 4. Zone division and adaptive transmission rates.

where λ denotes the thermal noise power at the receivers; $\wp$ is a constant threshold; $\Gamma(\mu, (\mu/\Omega)\lambda\wp)$ is the upper incomplete gamma function, denoted by $\Gamma(\mu, (\mu/\Omega)\lambda\wp) = \int_{(\mu/\Omega)\lambda\wp}^{\infty} t^{\mu-1}e^{-t}dt$.

We assume the wireless transceivers in vehicles can be adapted to support up to K discrete modulation rates based on the current V2V-link SNR, denoted by $H = \{\pi_1, \pi_2, \ldots, \pi_K\}$ with $\pi_1 < \pi_2 \ldots < \pi_K$. Specifically, if the current SNR is above the threshold $\wp_k$ and smaller than $\wp_{k+1}$, the modulation rate is set to as π_k, where we set $\wp_{K+1}$ as ∞. As such, based on (9), we have the expression that the transmission rate π_k for the current V2V link is selected with the probability

$$\Pr\{\pi_k\} = \Pr\left\{\wp_k < \frac{\Omega}{\lambda} < \wp_{k+1}\right\} = \begin{cases} \frac{\Gamma\left(\mu, \frac{\mu\lambda\wp_k}{\Omega}\right) - \Gamma\left(\mu, \frac{\mu\lambda\wp_{k+1}}{\Omega}\right)}{\Gamma(\mu)}, & k = 1, \ldots, K-1 \\ \frac{\Gamma\left(\mu, \frac{\mu}{\Omega}\lambda\wp_k\right)}{\Gamma(\mu)}, & k = K. \end{cases} \quad (10)$$

IV. Protocol Description

Due to the limited sojourn time and large number of contending vehicles within RSU's coverage, the download volume of individual vehicle is very limited, such that it is hard to enjoy the resource-consuming Internet services, such as video streaming. To remedy that, we propose ChainCluster to improve the Drive-thru Internet access service. ChainCluster is featured by its chain feature of vehicular cooperation behavior on the highways. Specifically, our proposal is composed of three phases defined as follows.

– *Cluster forming phase:* Upon entering the RSU's coverage, the tagged vehicle evaluates the performance of cooperative Drive-thru Internet and selects a number of vehicles to form a linear chain cluster for downloading sequentially from RSU.
– *Content download phase:* Within the RSU's coverage, the tagged vehicle allocates the download task according to the vehicular locations and mobility features. Then, the vehicles in the formed cluster download the corresponding parts of the file.
– *Content forwarding phase:* Once departure from the RSU's coverage, the tagged node collects the downloads from cluster members to recover the target file.

A. Cluster Forming Phase

Before entering into the RSU's coverage, the tagged vehicle coordinates to form a chain cluster. Several typical clustering approaches have been investigated in VANETs [9]–[11], where the basic idea about how to find the partners is similar. We focus on how to form a chain topology before arriving at RSU's coverage to keep it stable. To this goal, the tagged vehicle first broadcasts a cooperation request to the followed vehicles in its communication range. Vehicles who are willing to cooperate will make a confirmation to the tagged vehicle. After receiving the cooperation confirmations from the followed vehicles, the tagged vehicle will ask the confirmed partners to follow one by one after it and drive toward onto the cooperative download lane. Finally, the tagged vehicle needs to collect some simple mobility information of the members in the chain cluster (e.g., initial speed, intervehicle distance and position, etc.) to calculate the cluster size. Here, we implicitly assume that all vehicles are equipped with GPS devises to acquire the timely updates of the location information. This is a working assumption as GPS has already been a widely adopted technology, and it is also a key enabling component of vehicular communications.

Upon entering the RSU's coverage, the tagged vehicle evaluates the performance of cooperative Drive-thru Internet. The number of vehicles that needs to be requested to join ChainCluster depends on the target file size. If the needed vehicle number is larger than the vehicle number in the formed cluster by using the one-hop broadcasting cooperation messages, the tagged vehicle should adapt the download task to available cluster size. In addition, as the data download volume of a ChainCluster is closely related to the vehicle mobility, the cluster formation should also adapt the time-varying velocity of vehicles. In what follows, we provide the analysis to guide the tagged vehicles to evaluate the throughput of cooperative Drive-thru Internet and the number of vehicles in ChainCluster.

1) Analysis of CVN: Vehicles within RSU's coverage contend with each other to share RSU's bandwidth. For a vehicle V_i, Contending Vehicle Number (CVN) is defined as the number of vehicles that are concurrently within the RSU's coverage. In order to derive the achieved data download volume by individual vehicle, it is crucial to analyze the instant value of CVN. We derive the CVN of the tagged vehicle V_i at different time points. Note that, during the sojourn time within RSU's

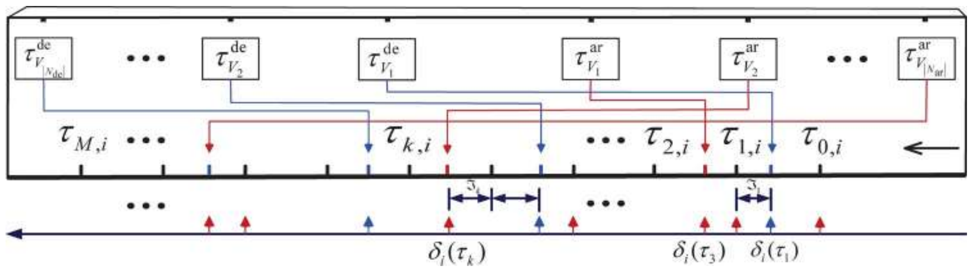

Fig. 5. Illustration of time sequence distribution for a tagged vehicle and the vehicles driving in the RSU's coverage.

coverage, CVN for V_i changes with time due to the dynamic arrivals and departures of vehicles to the RSU.

We first consider the single-lane highway scenario and divide the whole coverage range into M zones that is consistent with zones for adaptive data-rate transmission, denoted by $\Lambda = \{\Lambda_1, \Lambda_2, \ldots, \Lambda_M\}$, and shown in Fig. 4. Starting from the entrance point marked as ψ_0, the $M+1$ marked points are denoted by $\psi_0, \psi_1, \ldots, \psi_M$, respectively, which satisfy the condition that $\sum_{k=1}^{M} |\psi_k - \psi_{k-1}| = \zeta$, where ζ is the coverage range of RSU. Furthermore, we set the time when the tagged vehicle arrives at the entrance point ψ_0 as the initial time t_0, and set $t_0 = 0$ in our analysis. At this initial time t_0, there are μ_i vehicles already in the RSU's coverage and κ_i vehicles that followed behind. Let N_{de} and N_{ar} denote the set composed of the μ_i vehicles and the κ_i vehicles, respectively. To calculate the variations in the number of vehicles in RSU's coverage during V_i's sojourn time, we introduce more notations related to the sets N_{de} and N_{ar} as follows.

- N_{de}: Let $\psi_{t_0}^{\nu_j}$ be the location of the vehicle V_j in the set N_{de} at time t_0, i.e., the location of vehicle V_j as the tagged vehicle V_i just arrived at the entrance point ψ_0. Let $\zeta_{M,t_0}^{\nu_j}$ be the distance between the location of the vehicle V_j at time t_0 and the departure point ψ_M, denoted by $\zeta_{M,t_0}^{\nu_j} = |\psi_M - \psi_{t_0}^{\nu_j}|$. Let $\tau_{V_j}^{\mathrm{de}}$ be the time point that the vehicle V_j arrives at the departure point ψ_M, which can be calculated by (11). We define $T^{\mathrm{de}} = \{\tau_{V_1}^{\mathrm{de}}, \tau_{V_2}^{\mathrm{de}}, \ldots, \tau_{V_{|\mu_i|}}^{\mathrm{de}}\}$, $\mu_i = |N_{\mathrm{de}}|$, and $0 \leq \mu_i \leq \lceil \zeta/\Psi \rceil$. We assume that the value of μ_i can be obtained via a deployed camera within RSU's coverage.
- N_{ar}: Let $\psi_{t_0}^{\nu_k}$ be the location of the vehicle V_k in the set N_{ar} at time t_0, and let $\zeta_{0,t_0}^{\nu_k}$ be the distance between the location of the vehicle V_k at time t_0 and the entrance point ψ_0, denoted by $\zeta_{0,t_0}^{\nu_k} = |\psi_0 - \psi_{t_0}^{\nu_k}|$. Let $\tau_{V_k}^{\mathrm{ar}}$ be the time point that the vehicle V_k reaches to entrance point ψ_0, which can be calculated by (12). The set of driving time for all vehicles in N_{ar} is denoted by $T^{\mathrm{ar}} = \{\tau_{V_1}^{\mathrm{ar}}, \tau_{V_2}^{\mathrm{ar}}, \ldots, \tau_{V_{|\kappa_i|}}^{\mathrm{ar}}\}$, $\kappa_i = |N_{\mathrm{ar}}|$, and κ_i is the number of possible cooperative vehicles after the tagged vehicle's request, which depends on the factual scenario. Hence

$$\tau_{V_j}^{\mathrm{de}} \triangleq \left\{ \tau_j \middle| \sum_{q=1}^{\left\lceil \frac{\tau_j}{\Delta t} \right\rceil} \nu_j(t_0 + \Delta t \cdot q) \cdot \Delta t = \zeta_{M,t_0}^{\nu_j} \right\} \tag{11}$$

$$\tau_{V_k}^{\mathrm{ar}} \triangleq \left\{ \tau_k \middle| \sum_{q=1}^{\left\lceil \frac{\tau_k}{\Delta t} \right\rceil} \nu_k(t_0 + \Delta t \cdot q) \cdot \Delta t = \zeta_{0,t_0}^{\nu_k} \right\} \tag{12}$$

where ψ_M and ψ_0 are the departure point and the entrance point of RSU's coverage, respectively.

For the tagged vehicle V_i, we can get the set of individual running time point T^{tag} in the M zones of RSU's coverage, denoted by $T^{\mathrm{tag}} = \{\tau_{1,i}, \tau_{2,i}, \ldots, \tau_{M,i}\}$, where $\tau_{k,i}$ denotes the time point that the vehicle V_i leaves the kth zone, and can be calculated by

$$\tau_{k,i} \triangleq \left\{ \tau_k \middle| \sum_{q=1}^{\left\lceil \frac{\tau_k}{\Delta t} \right\rceil} \nu_i(t_{k-1,i} + \Delta t \cdot q) \cdot \Delta t = \zeta_{k,0}^{\nu_i} \right\}. \tag{13}$$

The data download volume by the tagged vehicle V_i per drive-thru is closely related to the variations of CVN in M zones of RSU's coverage, which only depends on the number of vehicles at every arrival time point and departure time point. To analyze the effects, we process the values calculated by (11)–(13) by three steps, which are introduced as follows.

Step 1) The three time sets are combined into a large set T, i.e., $T = \{T^{\mathrm{de}}, T^{\mathrm{ar}}, T^{\mathrm{tag}}\}$.

Step 2) We truncate the set T to make sure that its elements are within the fixed interval $\tau_{0,i}$, $\tau_{M,i}$, where $\tau_{0,i}$, and $\tau_{M,i}$ are the time point that the tagged vehicle V_i enters into and leaves from the RSU's coverage, respectively. For simplicity, we let $\tau_{0,i} = 0$.

Step 3) We chronologically reorder all elements in set T and denote the reordered set as $T' = \{\tau_1, \tau_2, \ldots, \tau_W\}$, where W is the number of elements in set T'.

To calculate the variations of CVN during the tagged vehicle's sojourn time, we design a moving time window to analyze the changing states in the set T', as shown in Fig. 5, and the size of time window is defined as $\Im_k = |\tau_k - \tau_{k-1}|$, $k = 1, 2, \ldots, W$. In fact, the sizes of W time windows are not the same, which can reflect each changing state for the contending number in M zones. To judge whether there exists a variation of CVN for the tagged vehicle V_i during the period of kth time window $\Im_k$, we define a decision function, which reflects whether one vehicle belonging to the set $N_{\mathrm{de}} \cup N_{\mathrm{ar}}$ leaves or arrives at the RSU's coverage. If one vehicle arrives at the RSU's coverage, the current CVN will be added by one, and vice versa. The decision function can decide the changing state of CVN at each discrete time point τ_k for the tagged vehicle V_i, which is denoted by $\delta_i(\tau_k)$, where $k = 1, 2, \ldots, W$, as follows:

$$\delta_i(\tau_k) = \begin{cases} -1, & \tau_k \in T^{\mathrm{de}} \\ 0, & \text{else} \\ +1, & \tau_k \in T^{\mathrm{ar}}. \end{cases} \tag{14}$$

According to (14), during the tagged vehicle V_i's sojourn time on single-lane highways, we can easily formulate the variations of CVN at individual time point τ_k in the set of T', denoted by $N_i(\tau_k)$. Furthermore, we can calculate the value of $N_i(\tau_k)$ in M different zones, i.e., at discrete time point τ_k, the CVN for the tagged vehicle V_i driving within the nth zone can be calculated, which is denoted by $N_i^n(\tau_k)$, $k = 1, 2, \ldots, W$ and $n = 1, 2, \ldots, M$, as follows:

$$N_i(\tau_k) = \mu_i + 1 + \sum_{j=1}^{k} \delta_i(\tau_j),\ \tau_k \in T' \tag{15}$$

$$N_i^n(\tau_k) = \{N_i(\tau_k) | \tau_{n-1,i} \le \tau_k \le \tau_{n,i}\}. \tag{16}$$

Our analysis of CVN for a single-lane highway scenario can be easily extended to the multilane highway scenario. For a multilane scenario with the highway lanes of P $(P = 2, 4, 6, \text{or } 8)$, the extended decision function to judge the variations in CVN for vehicle V_i driving in the nth zone can be derived by (17).

$$N_i^n(\tau_k) = \left\{ \sum_{j=1}^{P} \mu_{i,j} + 1 + \sum_{j=1}^{P}\sum_{r=1}^{k} \delta_{i,j}(\tau_r) | \tau_{n-1,i} \le \tau_k \le \tau_{n,i} \right\},\quad \tau_k \in T',\ n = 1, \ldots, M \tag{17}$$

$$\Phi_{v_i} = \sum_{k=1}^{W} \frac{\Im_k \cdot \{c_n | \tau_{n-1,i} \le \Im_k \le \tau_{n,i}\}}{N_i^n(\tau_k) \cdot P},\ v_i \in \Re,\quad n = 1, 2, \ldots, M \tag{18}$$

$$N_c = \left\{ \min\{\gamma\} | \gamma = 1, 2, \ldots, \kappa_i, \sum_{i=1}^{\gamma} \Phi_{v_i} \geqslant \Upsilon \right\} \tag{19}$$

However, in real applications, the traffic flows in different lanes are independent. For a tagged vehicle, it will be hard to collect enough information of traffic flow in different lanes for the analysis of CVN. For this consideration, we estimate the total CVN in the multilane scenario simply based on the result of single-lane scenario. For instance, we simply use $N_i^n(\tau_k) \cdot P$ to estimate the variations in the CVN for the tagged vehicle V_i at the time τ_k in the multilane scenario, where P is the number of highway lanes.

2) Analysis of Data Download Volume: Mathematically, the total data download volume by the tagged vehicle V_i per drive-thru can be calculated by (18), which denotes the average throughput when all vehicles within RSU's coverage fairly share the transmission opportunity. Let Υ be the required data download volume, the number of cooperative vehicles N_c can be calculated by (19). In a practical case, we can quickly estimate the number of required cooperative vehicles simply by $N_c \approx \lceil \Upsilon / \Phi_{v_i} \rceil$.

B. Content Download Phase

According to the analysis in the cluster forming phase, the tagged vehicle will select $N_c - 1$ vehicles that follow behind it and have similar mobility for cooperative content download. Once the tagged vehicle drives into RSU's coverage, it will subscribe to a file. To enable multiparty download, the file is divided into N_c chunks based on the evaluated download throughput of individual vehicle. The ongoing download content chunks are marked by $\{1, 2, \ldots, N_c\}$, which corresponds to the download file for the vehicles $V_1, V_2, \ldots, V_{N_c}$, respectively. Fig. 6 shows an example in which the chain cluster is composed of four vehicles, including the tagged vehicle at the cluster head. Upon receiving the application acknowledgement from RSU, all the vehicles driving into RSU's coverage can download the corresponding allocated tasks.

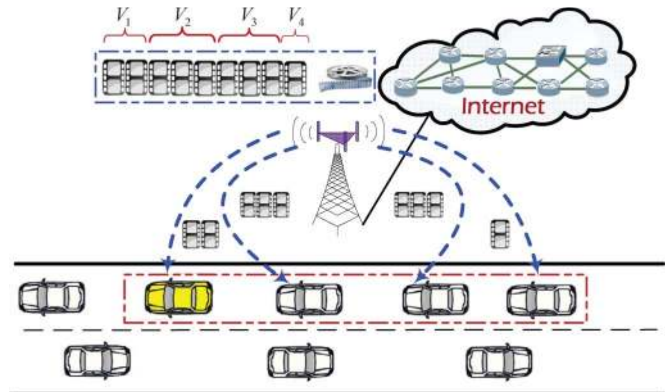

Fig. 6. Content division and cooperative download illustration.

C. Content Forwarding Phase

The ChainCluster adopts the contention-based MAC for distributed downloads forwarding on highways. We first evaluate the throughput of chain cluster under a cooperative content forwarding strategy. We consider that the vehicles apply the IEEE 802.11b distributed coordination function (DCF) scheme for MAC scheduling in ChainCluster. In addition, each packet is transmitted by means of request to send/clear to send (RTS/CTS) mechanism to eliminate the hidden terminals problem. We consider a constant contention window size for counting the backoff time, which is denoted as CW. Let $\mathfrak{T}$ denote the average transmission probability of each vehicle, and

$$\mathfrak{T} = \frac{2}{CW + 1}. \tag{20}$$

Different from that within RSU's coverage, the analysis of transmission contentions outside RSU depends on the vehicles' carrier sensing range. To calculate the number of vehicles that are contending the transmission channel in the vehicle transmission range, according to the vehicle number within RSU's coverage and the proportion to vehicles' carrier sensing range, we can estimate the vehicular number in the tagged vehicles' carrier sensing range, i.e., $\mathfrak{N}$ can be given as

$$\mathfrak{N} \approx \frac{\mathcal{S}}{\zeta} \cdot \mu_i \cdot P \tag{21}$$

where $\mathcal{S}$ denotes the vehicular carrier sensing range, and μ_i is the existing vehicular number within RSU's coverage when the tagged vehicle i first enters the RSU's coverage.

Let $\mathbf{P}_{\text{suc}}$ be the probability that one vehicle in the chain cluster transmits data on the channel successfully in the considered slot. Based on the contention mechanism, $\mathbf{P}_{\text{suc}}$ is given by

$$\mathbf{P}_{\text{suc}} = (N_c - 1) \cdot \mathfrak{T}(1 - \mathfrak{T})^{\mathfrak{N}-1}. \tag{22}$$

As shown in Fig. 7, the downloads are forwarded from the back to the head until all the downloads are received by the

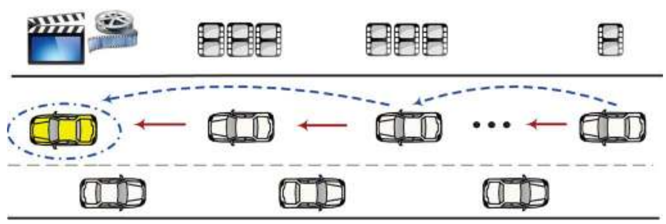

Fig. 7. Downloads forwarding in a vehicular chain-cluster.

tagged vehicle. We regulate that every vehicle only receives the forwarded content from the followed vehicles in the chain. Applying the results in [33], we can now evaluate the average MAC throughput from any vehicle i to vehicle j in the chain cluster, which is denoted as $\mathbf{Thr}$, mathematically, i.e.,

$$\begin{aligned}\mathbf{Thr} &= \frac{E[X_{\text{payload}}]}{E[Y_{\text{slot-time}}]}\\ &= \frac{P_{\text{suc}*}PA}{\underbrace{P_{\text{em}}*\sigma}_{E[T_{\text{empty}}]}+\underbrace{P_{\text{su}}*T_{\text{su}}}_{E[T_{\text{tran}}]}+\underbrace{(P_{\text{tr}}-P_{\text{su}})*T_{\text{co}}}_{E[T_{\text{coll}}]}}\end{aligned} \tag{23}$$

where $E[X_{\text{payload}}]$ denotes the average payload volume in the chain cluster transmitted successfully in a slot time, and PA is the package sizes including the package head. $E[Y_{\text{slot-time}}]$ denotes the average time slot length in the DCF scheme, including the average empty slot time $E[T_{\text{empty}}]$, the average successful transmission time $E[T_{\text{tran}}]$, and the collision time $E[T_{\text{coll}}]$. Based on the DCF performance analysis in [34], they can be given by

$$\mathbf{P}_{\text{em}}\sigma = (1-\mathfrak{T})^{\mathfrak{N}}\sigma_{\text{SlotTime}} \tag{24}$$

$$\begin{aligned}\mathbf{P}_{\text{su}}T_{\text{su}} &= \mathfrak{N}\mathfrak{T}(1-\mathfrak{T})^{\mathfrak{N}-1}\\ &\times\Bigg(RTS+3SIFS+4\sigma_{\text{propa}}+CTS\\ &\quad+ACK+DIFS+\frac{E(F)}{E(C)}\Bigg)\end{aligned} \tag{25}$$

$$\begin{aligned}(\mathbf{P}_{\text{tr}}-\mathbf{P}_{\text{su}})T_{\text{co}} &= \left(\left(1-(1-\mathfrak{T})^{\mathfrak{N}}\right)-\mathfrak{N}\mathfrak{T}(1-\mathfrak{T})^{\mathfrak{N}-1}\right)\\ &\times(RTS+DIFS+\sigma_{\text{propa}}).\end{aligned} \tag{26}$$

In (25), $E(F)$ is the average frame length, and $E(C)$ is the average modulation rate. Considering the maximal communication range of vehicles (300 m) and the intervehicle distance restriction, the vehicle can only connect with maximal two vehicles in the communication range. To calculate the downloads forwarding delay for the whole chain cluster, we can consider two strategies to forward the individual downloads, namely, one-by-one forwarding and the best vehicle selection forwarding. In an N_c-vehicle chain cluster, the N_c vehicles are ordered by $1, 2, \ldots, N_c$. According to the hop number of individual vehicle in the formed cluster, we can estimate the download forwarding time to retrieve a targeted file, denoted by $T_{\text{one-by-one}}$ and T_{best}, respectively. The download forwarding strategies in the chain cluster are described in the following.

– *One-by-one forwarding*: For this strategy, the downloads by individual vehicle are forwarded from the rear to the head, and the forwarding route for each vehicle is to forward the downloads to its next first vehicle in the front.

TABLE II
DEDICATED SHORT-RANGE COMMUNICATION DATA RATE AND SNR THRESHOLD SETTING

SNR Threshold (dB)	5	6	8	11	15	20	25	N/A
Date Rate (Mbps)	3	4.5	6	9	12	18	24	27

TABLE III
SETTING OF DCF AND HIGHWAY SCENARIO PARAMETERS

Parameters	Value	Parameters	Value
P_t	23 dBm	$G_t = G_t$	1
L	1	$h_t = h_t$	1
CW	$16, 32, 64, 128$	S	500 m
P	2,4,6	λ	-88 dBm
PA_i	1024,2048,5012 bits	H_i	400 bits
σ_{propa}	1 μs	$\sigma_{SlotTime}$	50 μs
$SIFS$	28 μs	$DIFS$	128 μs
ACK	37 μs	CTS	37 μs
$\nu_{\min}$	60 km/s	$\nu_{\max}$	120 km/s
η	$[-1, 1]$	ζ	$[600, 1000]$ m
$d^0_{i,i+1}$	$[120, 300]$	RTS	53μs

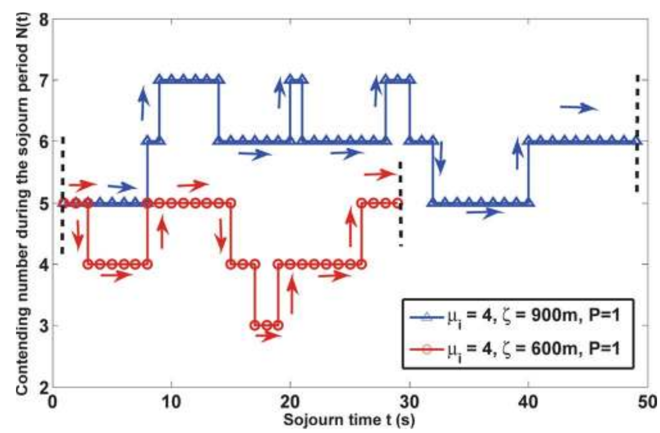

Fig. 8. Variations of CVN.

– *Best vehicle selection forwarding*: Compared with the aforementioned strategy, the vehicles try to forward the data to the farthest vehicle in the chain. Restricted by the communication range, each vehicle can forward the downloads as far as its next second vehicle in the front. The two strategies are presented as follows:

$$T_{\text{one-by-one}} = \left(\sum_{k=1}^{N_c}(k-1)\cdot\Phi_{\nu_k}\right)\Big/\,\mathbf{Thr} \tag{27}$$

$$T_{\text{best}} = \left(\sum_{k=1}^{N_c}\left\lceil\frac{(k-1)}{2}\right\rceil\cdot\Phi_{\nu_k}\right)\Big/\,\mathbf{Th}. \tag{28}$$

V. PERFORMANCE EVALUATION FOR CHAINCLUSTER

We conduct simulations to evaluate the performance of ChainCluster in highway scenarios using Matlab. The simulation settings, including the vehicular traffic parameters, V2R communication parameters, and V2V communication parameters, are specified in Tables II and III.

A. Demonstration for the Varying CVN

Fig. 8 shows the variations of CVN within RSU's coverage, which depends on current traffic state, including the vehicular driving speed, intervehicle distance, acceleration/

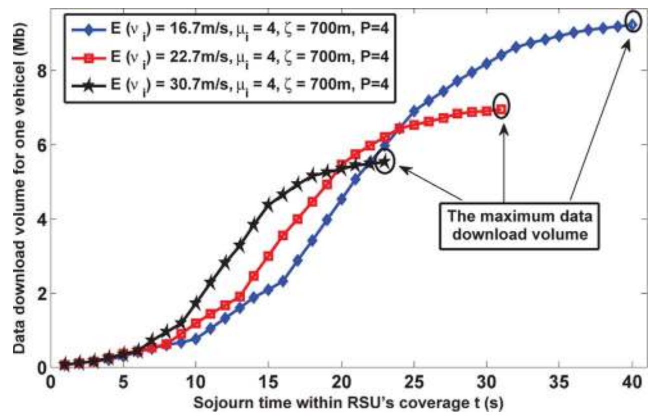

Fig. 9. Illustration for downloads under typical speeds.

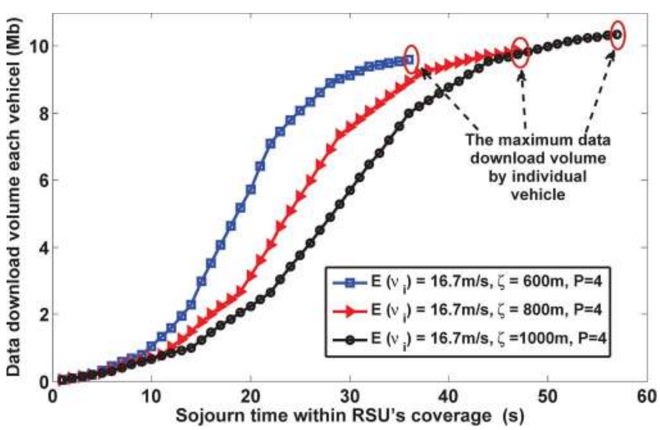

Fig. 10. Illustration for data downloading with different coverage.

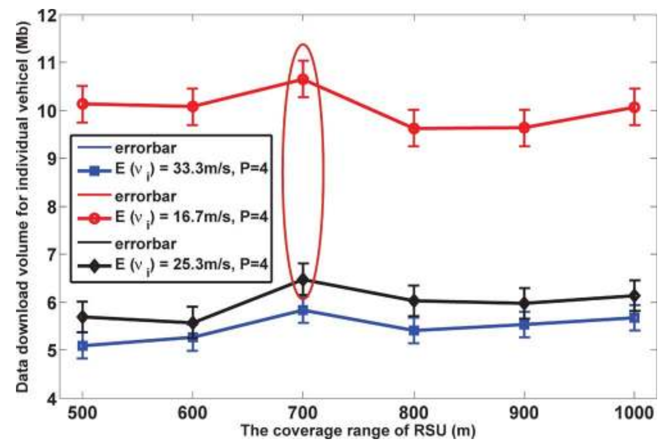

Fig. 11. Relationship among data download volume, speed, and coverage.

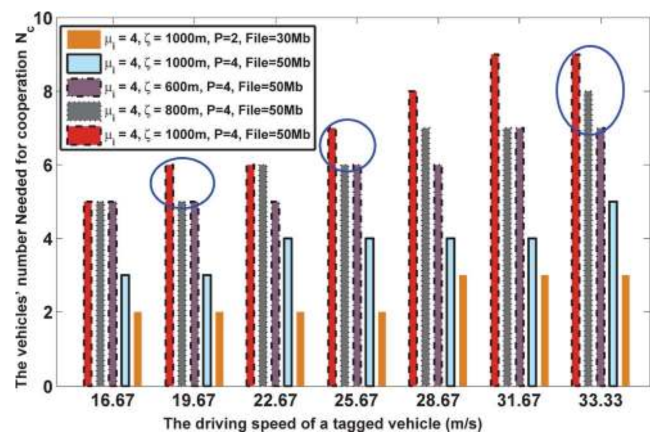

Fig. 12. Cooperative vehicular number under typical scenarios.

deacceleration, the number of highways lanes, and RSU's coverage. In the simulation, we set a simulation environment with ten vehicles in a line, and they will drive through the RSU's coverage; the other driving-related parameters are shown as following: the initial driving speed distribution is $(\text{rand}(1) + 1)^{*}16.67$; the intervehicle distance distribution is $(\text{rand}(1) * 0.25 + 1) * 120$; the acceleration/deceleration distribution is $\pm\text{rand}(1)$; the maximal and minimal speed constraints on highways is 16.67 and 33.33 m/s, respectively. As we can see, with the coverage of RSU to be 600 and 900 m, respectively, the CVN distribution at different sojourn time points are different, attributing to the enlarged RSU coverage. Considering a single-lane scenario and that the existing vehicular number is 4 when a tagged vehicle first drives into the RSU's coverage, the CVN distribution is among [3,5] and [5,7], respectively.

B. Performance Evaluation for the Data Download Volume and Cooperative Vehicle Number

Figs. 9–11 show the impacts of different parameters on the data download volume for a tagged vehicle per drive-thru. In Fig. 9, we can observe that, with the slowdown of vehicular velocity, the total download volume increases. The main reason is that the total sojourn time within RSU's coverage is prolonged. Interestingly, due to the adaptive transmission rates within RSU's coverage, Fig. 9 also shows the varied data download volume in different RSU zones, e.g., during the middle interval of sojourn time, the vehicle can download more data than the time points in the entrance part and departure part, which can be helpful to make strategies to download the maximal data download volume via controlling the vehicular speed in different zones. Fig. 10 shows the impact of the size of RSU's coverage on the data download volume. We can observe that a larger coverage for RSU does not contribute much to the increase in data download volume. When the RSU's coverage is enlarged by 67% from 600 to 1000 m, the download volume is only increased by nearly 8%. The main reason is the increased CVN as the coverage range is enlarged. Fig. 11 shows the impacts of the vehicular velocity and RSU's coverage on the data download volume of individual vehicle in different typical traffic scenarios. When the average driving speed for a tagged vehicle is 16.7, 25.3, and 33.3 m/s, respectively, the maximal data download volume can reach to 10.65, 6.48, and 5.84 Mb, respectively.

Fig. 12 shows the cooperative vehicular number under some typical traffic and download scenarios. We observe that, with the increase in mobility speed, the more vehicular number will be needed for cooperation, mainly due to the decreased sojourn time within RSU's coverage. For example, to download an 500-Mb file in Drive-thru Internet, the typical cooperative vehicle number value is among [5,9] for the four-lane highways. In addition, we also observe that the RSU's coverage makes slight contribution to the data download volume most of the time.

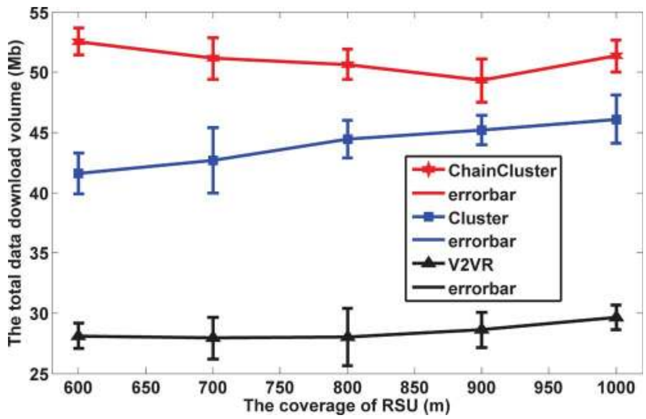

Fig. 13. Comparison of download performance of the proposed schemes.

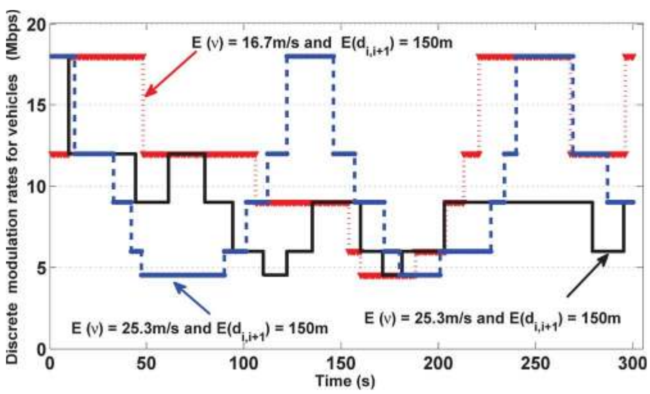

Fig. 14. Illustration of adaptive data-rate selection.

Fig. 13 shows the comparison of the total download volume by five cooperative vehicles in the proposed schemes, namely, ChainCluster, Cluster, and vehicle-to-vehicle relay (V2VR). In particular, the Cluster scheme is investigated in [9]–[11], where several mutual connected vehicles within RSU'S coverage are selected to cooperatively download. The V2VR scheme is discussed in [23], where the vehicle who wants to download the large-sized file will ask two vehicles as proxies: one in front of the vehicle and the other behind the vehicle. We observe that the ChainCluster can improve the download volume as more as 20.87% than the Cluster scheme. The main reason is that the ChainCluster can maximize the connection time via the linear chain topology. Although the cluster topology of V2VR is a linear chain, however, V2VR cannot satisfy the application requirements of different sized downloads, due to the limited cooperative number of vehicles. The maximal download volume of V2VR is less then 30 Mb.

C. Demonstration for the V2V Communication Model

Figs. 14, 15 show the process of adaptive data-rate selection and the different data-rate selection probabilities for free-driving vehicles, respectively. Fig. 14 shows that the selected transmission rate varies from 4.5 to 18 Mb/s. Fig. 15 shows the different transmission rates' selection probabilities for driving vehicles. The adaptive data-rate selection process and selection probabilities are closely related to the intervehicle driving distance on highways, which can also effect the download forwarding throughput for ChainCluster.

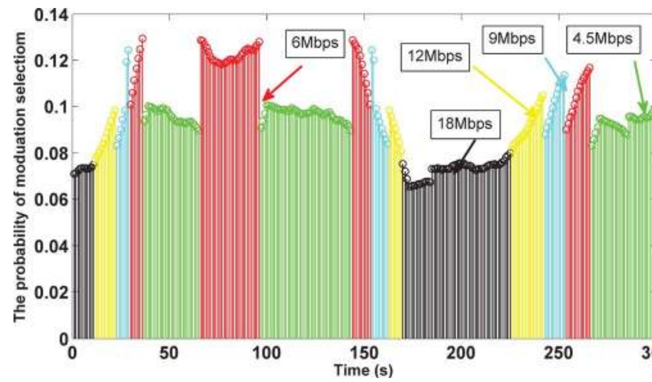

Fig. 15. Probability of different data-rate selection.

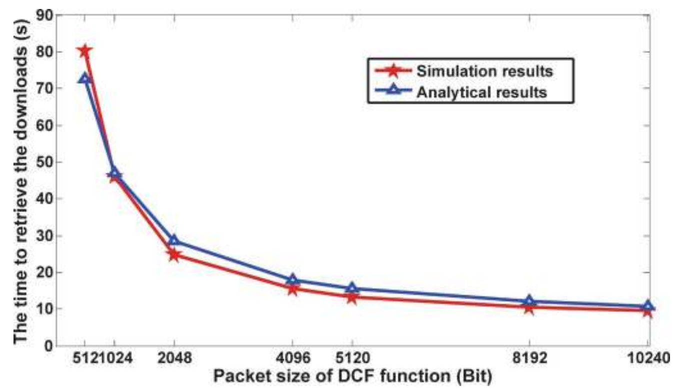

Fig. 16. Analytic results and simulation comparison for the data forwarding process.

D. Performance Evaluation for the Download Forwarding Time

We further demonstrate the impacts of various parameters on the download forward time. We simulate a case that five vehicles form a cluster and cooperatively download the file with 50-Mb size. After leaving the RSU's coverage range, the cooperating vehicles will forward their received data (i.e., 10-Mb data for each vehicle in this simulation) to the tagged vehicle (i.e., the vehicle at the head of the chain cluster). Fig. 16 shows the impacts of packet size on the download forward time. It is observed that, with the increase in effective packet size, the time taken to retrieve a completed file decreases, which is due to the increase in download forwarding throughput. For instance, the packet size increases from 512 to 1024 bits, the download forwarding time can be decreased by nearly 83.67%, and the simulation results of the whole file-retrieving time match with the analytical values very well. Fig. 17 shows how the CVN affects the download forwarding time for retrieving a 50-Mb file. We consider a Poisson distribution of vehicular number ranged from 5 to 20 (equally, from the single-lane to four-lane highway scenario). Obviously, the increase of CVN can prolong the download forwarding delay. For the case with 1024-bit package size, the download forwarding time is increased from nearly 45 to 129 s. Fig. 18 shows how the backoff window size in IEEE 802.11 DCF function affects on the download forwarding time for retrieving a 50-Mb file. As shown in Fig. 18, we can optimize the download forwarding time by choosing the optimal backoff window size, and in this scenario, the best window size is 32.

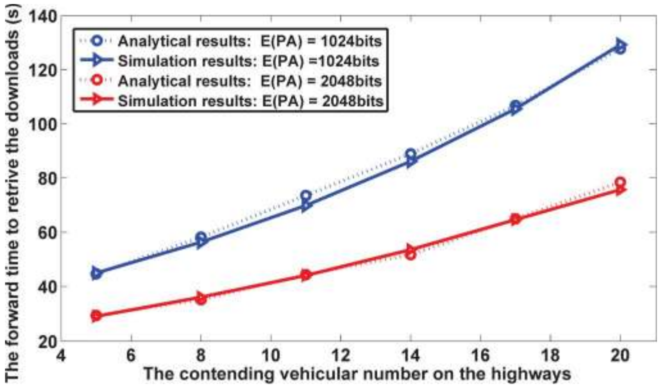

Fig. 17. Effect of CVN for data forwarding delay.

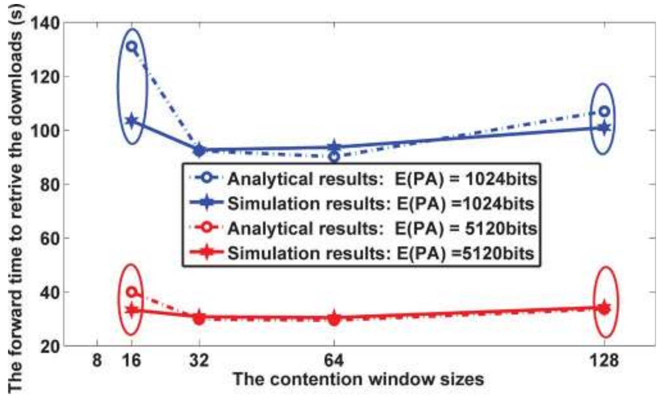

Fig. 18. Effect of contending window size for data forwarding delay.

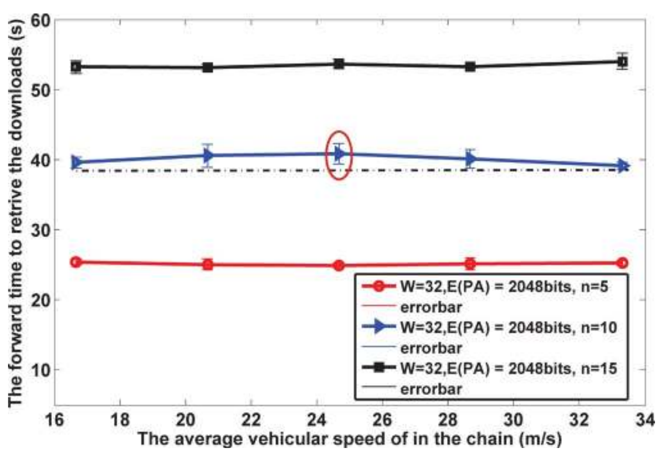

Fig. 19. Effect of vehicular driving speed for data forward delay.

Figs. 19–21 demonstrate the impacts of vehicular speed and intervehicle distance on the forwarding time. Fig. 19 shows that the vehicular driving speed affects less on the download forwarding time. The main reason is that the increase in driving speed cannot affect the selection of physical transmission data-rate, it makes less contribution to the data forwarding throughput of the transmission link. Fig. 20 shows that, with the decrease in intervehicle driving distance, the download forwarding delay is reduced. When the average intervehicle driving distance is enlarged from 130 to 260 m, the download forwarding delay is decreased by 11.1, 13.4, and 11.6 s, respectively. Fig. 21 shows the comparison of two download forward strategies: “one by one forward” and “best vehicle selection.” We observe that the latter can reduce the download forwarding

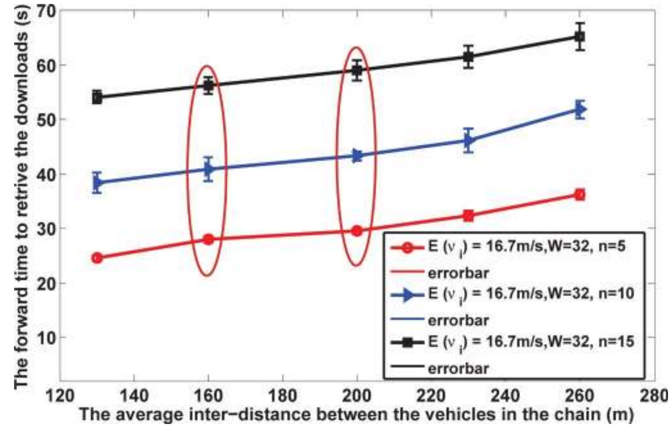

Fig. 20. Effect of intervehicle distance for data forward delay.

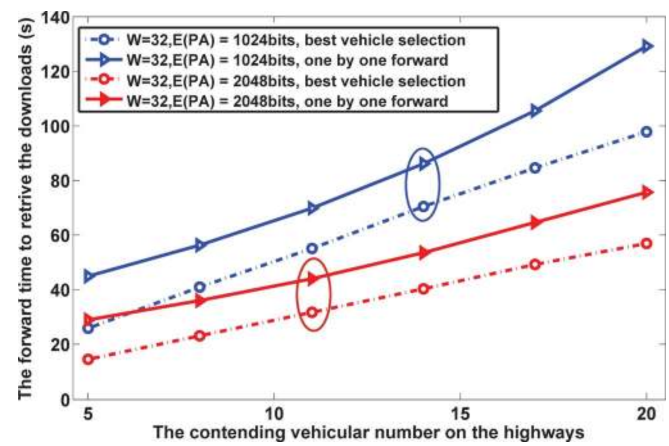

Fig. 21. Comparison of two considered forward strategies for data forward delay.

delay. In particular, we set a 300-m communication range of individual vehicle, and for the intervehicle distance restriction, each vehicle can connect, at most, the next two vehicles in the linear chain. If the data forwarding route is to find the further intervehicle distance each hop, for 1024-bit and 2048-bit package size settings, the download forwarding delay can be reduced by nearly 31 s and 18 s at most. Fig. 21 indicates that, with a high-contention environment (i.e., the large value of CVN), the best vehicle selection will achieve a larger reduction in download forward time.

VI. Conclusion

In this paper, we have proposed and analyzed the ChainCluster scheme for improving the Drive-thru Internet access service. The proposed ChainCluster scheme is a three-phase systematic solution for the cooperative content download and distribution among high-speed vehicles on highways. We have applied a microscopic mobility model, jointly considering two realistic mobility rules to analyze the CVN of a tagged download vehicle, which is crucial to evaluate the cooperative download performance in Drive-thru Internet. We have theoretically derived the data download volume by the tagged vehicle per drive-thru, and the results can be extended to multilane highway scenarios. Furthermore, we have proposed a download forwarding strategy for the ChainCluster based on the IEEE 802.11 DCF mechanism. From the perspective of real applications, we have derived the download forwarding time for different targeted downloads. Via the performance evaluation, we have observed that the vehicular velocity has significant impact on the data download volume, whereas the RSU's coverage only has slight effect on it. In addition, to quickly retrieve a file for the subscribed vehicle, we can achieve it by setting an optimized backoff window size, reducing the intervehicle distance under the safety distance restriction, and choosing the furthest vehicle in the transmission range for data forwarding.

A. Deployment Insight

The ChainCluster scheme provides a fundamental solution to the cooperative content download and distribution for highway vehicular communications, which shows its rationality, necessity, extendibility, and safety and efficiency in reality.

- *Rationality:* We consider that not all vehicles on the highways need to connect to the Internet every time meeting a Drive-thru Internet; hence, there exists potential vehicles to support cooperation in the ChainCluster scheme.
- *Necessity:* We consider the current data download volume of individual vehicle per drive-thru cannot satisfy the applications for large-sized file download; the ChainCluster scheme can at least support the resource-consuming service of one specific vehicle via utilizing other idle vehicles' download resource.
- *Extendibility:* The ChainCluster scheme can support the peer-to-peer (P2P) sharing scenario for highway VANETs, i.e., the tagged vehicle in the chain can be extended to one recommended representative with the same download interest and become an energetic mobile seed to provide the download for neighboring vehicles. The targeted download objective can be one selective popular file.
- *Safety and Efficiency:* The cooperative download lane can avoid blocking up the traffic of followed vehicles for free driving. The cooperative download rules can be implemented on the special lane to improve the throughput in intervehicle communications with safer guarantee, e.g., speed control and intervehicle distance adjustment, etc.

For our future work, we will consider a hybrid framework of wireless Internet access for vehicles.

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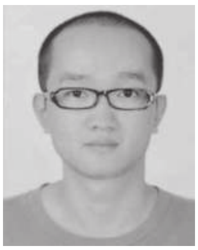

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