

Throughput Analysis of Vehicular Internet Access via Roadside WiFi Hotspot

Wenchao Xu, Member, IEEE, Weisen Shi, Feng Lyu, Member, IEEE, Haibo Zhou, Member, IEEE, Nan Cheng, Member, IEEE, Xuemin (Sherman) Shen, Fellow, IEEE

Abstract—Roadside WiFi network has been widely considered for the drive-thru Internet access. However, the data throughput is significantly affected by the *access procedure* which includes the steps of association, user authentication and assignment of network parameters such as Internet Protocol (IP) address. In this paper, we investigate the throughput performance of the drive-thru Internet considering the impact of the *access procedure*. Particularly, a three dimensional (3D) Markov model is proposed to analyze the relationship between the vehicle's location and the accomplishment of the *access procedure* that involves the exchange of the management frames under different conditions, such as number of contending WiFi clients, number of management frames, and their drop rate due to channel error, etc. We also study two access schemes, namely, Hotspot 2.0 and WPA2-PSK, to show how different access protocols can affect the throughput performance. We conduct extensive simulations to validate our analysis, which could provide provident insight for future development of vehicular networks.

Index Terms—Internet access, Authentication, Vehicular networks, Markov chain, Drive-thru Internet

I. INTRODUCTION

Internet of Vehicles (IoVs) are expected to provide high rate Internet connections, where various applications can be employed in vehicles to provide immersive experience for drivers and passengers [1] [2]. For example, Intelligent Transportation (ITS) system can collect and disseminate the vehicles' internal and external conditions via the Vehicle-to-Infrastructure (V2I) connections to improve the road efficiency and driving safety level [3] [4]. Besides, with the Internet access, a myriad of infotainment applications, such as video streaming, web page surfing, etc., are becoming indispensable for passengers. Furthermore, some data-craving applications, such as High Definition (HD) map, autonomous driving, etc., is expected to be realized via the high bandwidth connection. It is predicted that the global vehicular data traffic will reach 300 Zettabytes by 2020 [5], which can cause a great pressure to current Internet access technologies for vehicles [6]. Cellular networks are initially adopted for Internet access for vehicles. However, the costs of downloading/uploading all traffic to cellular networks are usually not affordable for vehicle users.

Copyright (c) 2015 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

W. Xu, W. Shi, F. Lyu (corresponding author), N. Cheng and X. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada, N2L 3G1, (email: {w74xu, w46shi, f2lyu, n5cheng, sshen}@uwaterloo.ca)

H. Zhou is with the School of Electronic Science and Engineering, Nanjing University, Nanjing, China, 210093, (email: haibozhou@nju.edu.cn)

In addition, cellular network capacity will be drained up in dense condition where lots of vehicles are requesting heavy data tasks [7]. To overcome the drawbacks of cellular Internet access, different wireless technologies have been proposed to provide alternate choices. Zhou *et al.* used the TV white space (TVWS) spectrum enabled infostation to disseminate the multimedia content [8]. However, the adoption of TVWS is restricted by the geo-location where the regulation and policy of using TVWS spectrum varies place by place. Wu *et al.* adopted the heterogeneous small cells to offload the cellular traffic, however, it requires frequent vertical and horizontal handoff for vehicle users due to their high mobilities [9]. Ligo *et al.* utilized the Dedicated Short Range Communications (DSRC) to offload the vehicular traffic to Internet [10]. However, the link rate is limited as the DSRC bandwidth is only half of 802.11a. Luo *et al.* investigated the inter-vehicle performance based on the visible light communication (VLC) [11], which is greatly affected by the day light noise and line-of-sight condition and the network deployment is difficult.

WiFi can overcome the restriction of the above radio technologies. First, WiFi has been widely used for Internet access around the world for years. It is predicted that by the year of 2021, 73% percent of the global Internet traffic will be served by WiFi networks [12]. WiFi devices are universally compatible and the unlicensed spectrum is used that are not restricted over all regions of the world. Compared with licensed spectrum based technologies, e.g., LTE-V2X, WiFi device does not need a permission, and different generation WiFi can communicate with each other without upgrading their devices. Secondly, WiFi has significant link throughput. The latest 802.11ac protocol can achieve the peak link rate around 1 Gbps [13], which provides enough capacity for vehicles in a WiFi cell even in dense condition. Furthermore, unlike deploying TVWS station or consuming in cellular networks, the economic cost of operating WiFi networks are relatively low. A roadside WiFi network can be agilely setup using commercial off-the-shelf devices and open source software, which is much cheaper than building infrastructures for macro-cells, e.g., LTE-V2X base stations [14].

There have been extensive research works on roadside WiFi Internet access for vehicles. Ott *et al.* first proposed the concept of 'Drive-thru Internet' that utilize a 802.11b hotspot to provide temporal Internet access for drive-by vehicles [15]. The conducted road test showed that considerable data traffic can be transmitted between the roadside hotspot and the vehicle, which demonstrated that it is feasible to provide

Internet access for vehicles by WiFi technologies. Mahajan *et al.* measured the end-to-end connectivity between moving vehicles and the roadside WiFi Access Points (APs)¹. And the throughput performance between the AP and the moving vehicles are also investigated on different regions [16]. Cheng *et al.* adopted the queueing model to analyze the traffic offloading performance for vehicles using the intermittent roadside WiFi networks. The relationship between the offloading effectiveness and the average service delay of the data tasks are analyzed [17]. Similarly, Zhou *et al.* proposed a cluster based scheme to conduct cooperation between multiple roadside APs to deliver content to vehicles [18]. However, existing works seldom consider the *access procedure* that a vehicle user has to accomplish before he/she can actually access to Internet via a roadside hotspot [19]. The *access procedure* generally contains the following steps:

1) Network Detection: Before access to the roadside WiFi network, the vehicle should percept the existence of the network via beacon frames exchange or other query protocols (e.g., the Access Network Query Protocol (ANQP) of Hotspot 2.0) [20]. This step is essential for vehicles to get the information about the wireless link parameters, e.g., 802.11 radio channel, supported rates, SSID, etc., and the backhaul information like authentication method, current load, etc. The information can also help the vehicle to select a proper nearby AP.

2) User Authentication: It is required to setup reliable and secure wireless connections between the AP and its users. WiFi operators use the authentication step to identify qualified users and prevent unauthorized users from stealing the network resources, while WiFi users rely on this step to protect their communication privacy. There are several authentication mechanisms which are applied in different scenarios. Commonly, webpage/SMS verifications are used in some public places such as airports, malls, etc. And WPA2-PSK are often used in residential areas. WPA2-802.1X is used in commercial WiFi access or enterprises, e.g., eduroam [21]. From the measurement results in [19], it can be observed that the delay caused by the *access procedure* is mainly from the user authentication step, which takes up the majority part of the management frames and also introduce possible negotiation overhead with remote authentication server. Sophisticated authentication schemes usually require more management frames to be exchanged between the WiFi client and the authentication server, which consumes longer time and thus the overall throughput that the vehicle can achieve would be reduced.

3) Network Parameters Assignment: To communicate with other entities on Internet, it is required that the associated WiFi users to have an IP address. Dynamic Host Configuration Protocol (DHCP) protocol is often used to assign the IP address for WiFi users dynamically. In some conditions, the vehicle might need to configure extra network settings². Such steps require a number of management frames to be exchanged

between the vehicle, hotspot and remote servers.

In practice, the above steps are necessary to setup effective and reliable Internet connection for vehicles. However, most previous research works and conducted experiments have neglected these steps. In [15], Ott *et al.* used an open WiFi hotspot without verifying user credential before allowing network access, i.e., no user authentication step is included. And a static IP address was assigned to the vehicle who could access to the network immediately when the vehicle drives over. The experiment in [22] did not include the authentication step, while the measurement result showed that the DHCP latency could be several seconds. Mahajan *et al.* also did not consider the overhead of authentication and IP address acquisition in their measurements in [16]. The analytical works from [17], [18], [23], [24] assume that Internet can be accessed as soon as the vehicle drives into the cell coverage areas, where the impacts of the *access procedure* were omitted.

A vehicle cannot access to Internet via the roadside WiFi AP until the *access procedure* is accomplished. Since the sojourn time of a vehicle within the WiFi coverage area is limited, a fast access procedure will leave more time for downloading/uploading Internet data, and vice versa. The accomplishment of the *access procedure* can be deferred in the following conditions. First, when the number of other WiFi clients, e.g., other vehicles, are associated to the same AP increases, the finish of the procedure will be deferred as the exchange of all the management frames requires more time when contending channel resource with its peers. Secondly, when the channel quality degrades, each management frame may require more retransmission attempts as the packet error rate increase. Besides, the parameters of the IEEE 802.11 distributed coordination function (DCF), e.g., minimum window size, back off stage number, may also change the DCF process for transmitting each management frame [25], which lead to different consequence of a transmission attempt, and thus affect the accomplishment of the *access procedure*. Furthermore, different authentication methods require the vehicle to exchange different set of management frames with the AP and authentication server, and thus the steps of user authentication are different.

In this paper, we investigate the throughput performance of drive-thru Internet considering the accomplishment of the practical *access procedure*. Particularly, our objective is to find the relationship between the average amount of Internet traffic a vehicle can download/upload via a roadside AP, and environmental and protocol execution conditions such as the management frame drop rate due to channel error, number of the neighboring vehicles, 802.11 DCF parameters (e.g., back off stage and minimum window size) and the adopted authentication protocols. The main contributions of this paper are highlighted as follows: First, we apply a 3D Markov process to model the *access procedure* between the drive-by vehicle and the roadside AP while the vehicle moves through the coverage area, whereby the relationship between the vehicle's position and the process of the *access procedure* is investigated. Secondly, we validate and compare the throughput of the drive-thru Internet and find out the throughput loss due to the *access*

¹We might use the terms of hotspot and AP interchangeably in the paper.

²For example, apply VLAN settings to divide the broadcast domain of several sub-nets.

procedure in various conditions. Thirdly, we discuss the future application of our model, which is expected to be an important tool in future vehicular communication protocol research and development.

The remainder of the paper is organized as follows. Section II shows the related works. The system model is presented in Section III. The 3D Markov model and the according analysis are demonstrated in Section IV, while the simulation verification and potential application of the model are shown in Section V. Finally Section VI concludes the paper.

II. RELATED WORKS

To provide Internet access by roadside APs, the impacts of the *access procedure* has been brought to the forefront for vehicle users. Fast access protocols have been proposed to reduce the round trips when exchanging the required management frames. For example, the IEEE 802.11r amendment reduces the number of authentication frames to be exchanged by caching the pairwise master key among different APs so that the time to accomplish the *access procedure* can be reduced [26]. Lopez *et al.* utilized the network layer information to optimize the network access in handoff process [27]. Such pre-authentication mechanisms require the cooperation between different APs or subnets, which is difficult in real deployment. And the overhead of network detection via query or beaconing, and network parameters assignment were not considered. Shin *et al.* utilized a selective channel scanning method to shorten the network detection delay and thus the access overhead can be reduced [28]. However, the authentication step which takes the majority part of the access delay was not considered. In fact, to eliminate the impacts of the *access procedure*, which are difficult to evaluate, most experiment and measurement of the WiFi connection between vehicles and APs in literature works applied the open association [15] [29], static IP address setting [16] [30] and without authentication step [22] [31]. Lu *et al.* argued that the time for *access procedure* cannot be neglected due to high mobility of vehicles, which can take up to ten or more seconds [1].

In [19], the *average access delay*, defined as the duration to accomplished the *access procedure* is analyzed and measured, which can be regarded as the metric to evaluate the throughput performance of the drive-thru Internet, as higher delay will cause less Internet connection time, and thus reduce the data amount that transmitted between the vehicle and the AP. However, given the value of *average access delay*, it is still not enough to obtain the actual throughput performance since the WiFi link rate is varying with distance between the vehicle and the AP [14]. Generally, the Probability Density Function (PDF) $f_a(t)$ is required to calculate the average throughput D_a , which is difficult to obtain:

$$D_a = \int_t^{\frac{L}{v}} \bar{R}(vt, n) f_a(t) dt \quad (1)$$

where $\bar{R}(x, n)$ is the average WiFi link rate when the distance between the vehicle and AP is x , and v , L are the vehicle velocity (assuming that vehicle velocity does not change in the coverage area) and the coverage range respectively and

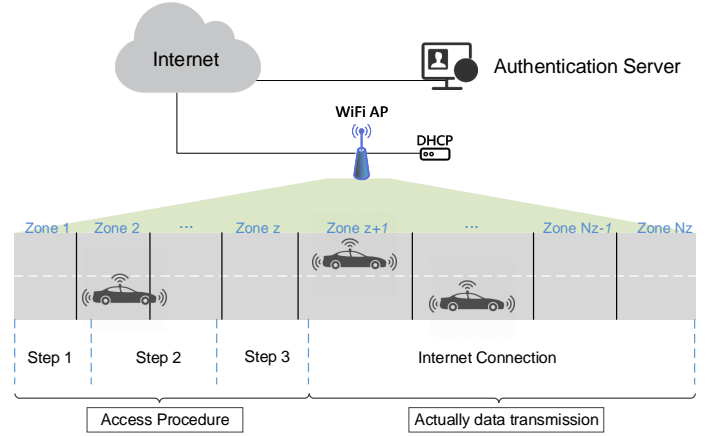


Fig. 1: System model

n is the number of co-associated WiFi clients. In [32] the management frame transmission during the *access procedure* is demonstrated as the state transition of a 2D Markov process as the vehicle drives through different zones of the coverage area. However, the factors to fulfill each management frame, such as number of co-associated WiFi clients, management frame drop rate due to channel error, etc., were not considered. Instead of calculating $f_a(t)$, we adopt a 3D Markov process to obtain the throughput performance by study the position transition upon the *access procedure* with the consideration of the transmission contention for each management frame, which is affected by the number of clients in the same cell, management packet drop rate due to channel loss, and the 802.11 back off process.

III. SYSTEM MODEL

The system model is elaborated in the following parts, including the network model, zone transition model and Medium contention model.

A. Network model

As shown in Fig. 1, a stretch of road is covered by a WiFi AP located at the roadside. As soon as the vehicle drives into the coverage area where the Signal-to-Noise Ratio (SNR) grows to certain level, the *access procedure* is started, and before its accomplishment the vehicle cannot transmit any data frame to the AP. Two common kinds of access protocols are considered in the *access procedure*, i.e., the WPA2-PSK and Hotspot 2.0³. The total number of the management frames during the *access procedure* for the two protocols are different, and in following analysis it is denoted by N_A .

1) *WPA2-PSK*: WPA2-PSK is widely adopted in domestic WiFi networks, which verifies the user name and password locally to allow users to access to the WiFi resource. WPA2-PSK requires limited frames to be exchanged and no backhaul delay is involved. We use traditional beaconing schemes for the initial handshake between vehicle and AP for network detection.

³The Hotspot 2.0 specifies more contents other than the *access procedure*, such as the QoS mapping, online sign up, etc. [14].

TABLE I: Management frames of access protocols

Access Scheme	Hotspot 2.0			WPA2-PSK		
	Protocol	N_A	Backhaul delay	Protocol	N_A	Backhaul delay
AP Detection	ANQP handshake	2	N	Beaconing	2	N
Authentication	802.1X	27	Y	PSK	8	N
IP address	DHCP	2	N	DHCP	2	N

2) *Hotspot 2.0*: Hotspot 2.0 is put forward to provide the seamless roaming for WiFi users [20]. WiFi network is detected by exchanging the ANQP frames with the network users. Hotspot 2.0 adopts the 802.1X authentication method, which requires the handshake between the vehicle user and the remote authentication server, and thus introduce the backhaul delay to generate some management frames.

The IP address is assigned if the vehicle is successfully authenticated via a local DHCP server, which requires two DHCP request and reply frames to be exchanged⁴. The information of the management frames for both two access schemes are summarized in Table I.

Assuming there are already n WiFi clients (except the approaching vehicle, can be other vehicles or other types of users) associated to the same AP and keep on sending packets to it, i.e., under a saturated traffic situation. As the *access procedure* takes places in the edge of the network coverage area, the transmission of the management frames is likely to fail due to the unreliable channel condition, whose probability is denoted by β . According to 802.11 protocol, the link modulation rate depends on the SNR level, which is mainly determined by the distance between the AP and the vehicle [24] [33]. The link rate is assumed to be the same within a specific zone in the coverage area, which is defined in the following subsection.

B. Zone model

Inspired by [24] [34], the road stretch covered by the WiFi AP can be divided into N_z zones based on the modulation link rate between the vehicle and the AP. And as the vehicle drives through the coverage area, it traverses the zones consecutively. The duration the vehicle stays in an arbitrary zone z , denoted by t_z , equals to d_z/v , where d_z is the size of the zone. The link rate when the vehicle is in zone z is denoted by r_z . Similar to [24], the time a vehicle stay in each zone is approximated as an geometrical variable with mean of t_z . Within an relatively small duration δ , the probability that the vehicle in zone z will transit to the next zone $z + 1$ equals to δ/t_z , and two consecutive transitions are independent. If the vehicle velocity changes across different zones, the average sojourn duration inside each zone would also change, so does the corresponding zone transition probability. Without loss of generality, we assume that the velocity remains the same and t_z is determined solely by the value of v and sizes of zones.

⁴It is also possible to deploy a remote DHCP server to assign the IP address while the AP is served as an DHCP proxy. Such case requires more DHCP management frames and introduce backhaul delay

C. Medium contention model

To investigate the affect of co-transmission from contending WiFi clients, e.g., vehicles associated to the same AP, the media access procedure for each management frame is also investigated. We apply the 802.11 DCF without employing the RTS/CTS scheme, and the minimum contention windows size is denoted by w , while the number of the back off stages is denoted by m ⁵.

IV. 3D MARKOV CHAIN BASED THROUGHPUT ANALYSIS

In this section, we adopt a 3D Markov chain to demonstrate the proceeding of the access procedure, which includes the dimensions of back off procedure, management frame index sequence and zone transition. We first build a 1D Markov chain for the back off stage transition when transmitting a certain management frame, and then expand it to a 2D Markov chain by considering the sequence of the management frames. And by sampling the beginning and ending moments of each status in this 2D Markov chain for the zone transition process, we finally form a 3D Markov chain model, which is used to calculate the relationship between the vehicle position and the accomplishment of *access procedure*, which is then used to obtain the drive-thru Internet throughput.

A. Dimension of back off procedure

Consider the k th management frame during the *access procedure*, which should be generated before transmission. The frame generation involves the local protocol process, potential backhaul handshake, and network framing. The whole procedure is defined as the *core process*, after that the frame is sent based on the 802.11 DCF, which incurs the back off procedure with a random back off counter C_i at stage i , $i \in [0, m - 1]$, and the initial stage i is set to 0:

- 1) The back off counter C_i is uniformly selected from $[0, w * 2^i - 1]$, where w is the minimum window size.
- 2) If the channel is sensed idle, then decrease the back off counter per time slot; if the channel is busy, then freeze the back off counter.
- 3) If the C_i decreases to zero, then attempt to transmit the frame to air;
- 4) If the transmission fails either due to collision or channel error, then increase the stage value i by one until to its maximum value, and go to step 1).⁶

⁵Different values of w and m may be employed to provide differential services, e.g., for delay-sensitive voice traffic [35], however in this paper we consider all WiFi clients use the same w and m values.

⁶There is no try limit to transmit a frame.

5) If the transmission is successful and the corresponding ACK is received, then jump to the frame generation (*core process*) of the next management frame.

As the frame generation is independent with the frame transmission, and any transmission attempt is independent with the previous one, by sampling the end moment of each transmission attempt, the transition of the back off stage value i forms a discrete time Markov Chain [36], as demonstrated in Fig. 2, the triangle represents the status of *core process*, i.e., management frame generation, whose duration is denoted by $t_{c,k}$, while the circle represents the i th back off stage.

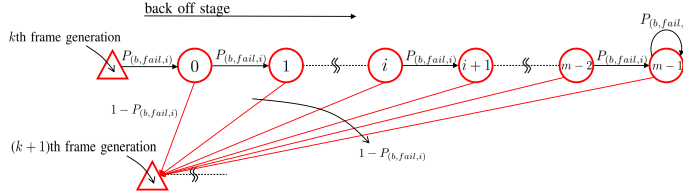


Fig. 2: Dimension of back off procedure

The one-step transit probability when transmitting k th management frame, denoted by $P_{(b,fail,k)}$ during the back off procedure can be calculated via the equations in Bianchi's method [36]:

$$\tau_k = \frac{2(1 - 2P_{(b,fail,k)})}{(1 - 2P_{(b,fail,k)})(w + 1) + P_{(b,fail,k)}w(1 - (2P_{(b,fail,k)})^{m-1})} \quad (2a)$$

$$\rho_k = 1 - (1 - \tau_k)^n \quad (2b)$$

$$P_{(b,fail,k)} = 1 - (1 - \rho_k)(1 - \beta_k). \quad (2c)$$

where ρ_k is the probability of collision for a transmission attempt of the k th frame, β_k is the probability that the transmission of k th management frame fails due to channel error. Given current stage is i , the next stage will be $i + 1$ if the transmission fails, otherwise it will directly jump to the *core process* of the $(k + 1)$ th management frame.

The average time during the status of the k th frame's *core process*, $\mathbb{E}(t_{c,k})$, depends on the access protocol and the backhaul network status, and can be measured from a real WiFi system [19]. The average time during each back off stage i can be calculated by

$$\mathbb{E}(T_i) = \mathbb{E}(T_{idle}) + \mathbb{E}(C_i) * \mathbb{E}(T_\sigma) + P_s * T_s + P_{us} * T_{fail} \quad (3)$$

where $\mathbb{E}(T_{idle})$ is average duration to sense the channel to be idle and then the back off procedure can be invoked, which can be approximated to the time for successfully transmitting a data frame in saturated condition:

$$\mathbb{E}(T_{idle}) = T_h + \frac{L_d}{r_{d,z}} + \text{SIFS} + \frac{L_{ack}}{r_{ack}} \quad (4)$$

T_h is the time to transmit the physical header section of the wireless frame, such as the PLCP field, PLME field, etc. L_d is the length of the data frame and is assumed to be identical for all WiFi clients. $r_{d,z}$ is the modulated link rate of the data frame when the vehicle is located at zone z . SIFS is the length of the Short Interframe Space as specified in 802.11 protocol. L_{ack} and r_{ack} are the length and the rate of the ACK frame

respectively.

The average value of the back off counter at stage i in equation (3) can be calculated as below since the counter is uniformly distributed in $[0, w * 2^i - 1]$

$$\mathbb{E}(C_i) = \frac{1}{2}(w * 2^i - 1) \quad (5)$$

$\mathbb{E}(T_\sigma)$ represents the average time spent to decrease one back off counter. Denote the length of a idle time slot in 802.11 protocol by σ , and T_σ may include several σ and back off durations, which can be calculated by considering three conditions. First, in a given slot, it is possible that all the other vehicles are not transmitting in the given time slot, whose probability is denoted by p_0 , and in this situation, the time to decrease one back off counter equals to σ . Secondly, it is also possible that there is only one vehicle is transmitting in the given time slot with the probability of p_1 , and if the transmission is successful, then it requires $t_{1,s}$ to decrease on back off counter:

$$t_{1,s} = T_h + \frac{L_d}{r_{d,z}} + \text{DIFS} + \text{SIFS} + \frac{L_{ack}}{r_{ack}} \quad (6)$$

And if the transmission fails due to channel loss with the probability of β_d , there is no ACK frame and thus it requires $t_{(1,fail)}$ to decrease one back off counter:

$$t_{(1,fail)} = T_h + \frac{L_d}{r_{d,z}} + \text{DIFS} \quad (7)$$

Thirdly, if there are two or more other vehicles are transmitting, which means there will be transmission collision, whose probability is denoted to $p_{(2+)}$, then it also requires $t_{(1,fail)}$ to decrease one back off counter. And $\mathbb{E}(T_\sigma)$ can be calculated by

$$\begin{aligned} \mathbb{E}(T_\sigma) &= p_0\sigma + p_1t_{1,s}(1 - \beta_d) + t_{(1,fail)}[p_{(2+)} + p_1\beta_d] \\ &= (1 - \rho_k)\sigma + p_1(1 - \beta_d)(\text{SIFS} + \frac{L_{ack}}{r_{ack}}) \\ &\quad + (p_1 + p_{(2+)})t_{(1,fail)} \end{aligned} \quad (8)$$

where p_1 can be obtained by

$$p_1 = C_n^1 \tau_k (1 - \tau_k)^{n-1} \quad (9)$$

and $p_1 + p_{(2+)}$ equals to the probability that there are one or more other vehicles are transmitting, which is ρ_k .

The probability that the management frame is transmitted successfully, denoted by P_s in equation (3), equals to $1 - P_{(b,fail,k)}$, while P_{us} equals to $P_{(b,fail,k)}$. The air time spent to successfully transmit the management frame T_s can be obtained via

$$T_s = T_h + \frac{L_k}{r_k} + \text{SIFS} + \frac{L_{ack}}{r_{ack}} \quad (10)$$

where L_k is the length of the k th management frame. And the air time spent if the transmission fails T_{fail} can be obtained by

$$T_{fail} = T_h + \frac{L_k}{r_k} * \frac{\beta_k(1 - \rho_k)}{P_{b,fail,k}} + \frac{L_d}{r_{d,z}} * \frac{\rho_k}{P_{(b,fail,k)}} \quad (11)$$

where the second item in the above equation is an approximation of the air time to deliver the management frame given the condition that the transmission fails due to channel error, while the last item is the air time to deliver the data frame, as the transmission failure is caused by collision⁷.

B. Dimension of management frame delivery sequence

The frame generation and transmission of the $(k+1)$ th management frame only depends on the previous k th management frame, and thus the frame index, namely, k , forms a discrete Markov chain that takes the value from $[1, N_A]$, as shown in Fig. 3. The last ‘accessed’ status of ‘ $N_A + 1$ ’ indicates that all the management frames are exchanged, i.e., the *access procedure* has been accomplished. A similar model based on the consecutive delivery of the management frames can be found in [19], where the accuracy is verified both in numerical simulation and experiment.

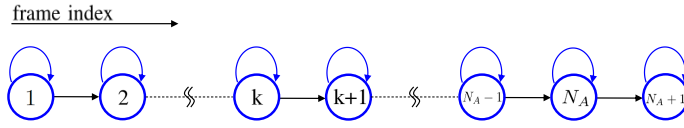


Fig. 3: Dimension of frame delivery sequence

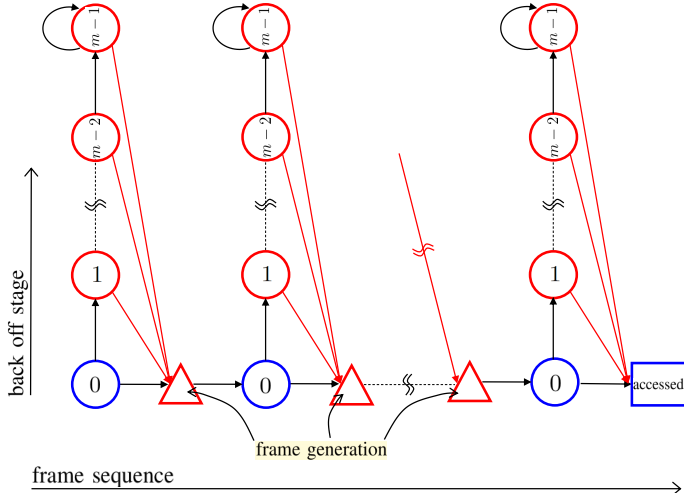


Fig. 4: 2D Markov chain for back off procedure and frame delivery sequence

Since the transmission of each management frame is independent with each other, i.e., the back off stage altering of one frame is independent with another, thus, the Markov chain in Fig. 2 and the Markov chain in Fig. 3 together can form a 2D Markov chain of size $2N_A$ by m , which is shown in Fig. 4. In the dimension of the back off procedure, there are m status, while in the dimension of the frame sequence, there are $2N_A$ status, including the *core process* except the first frame (beaconing or ANQP query). And without loss of generality, the status of the vehicle can be denoted by a vector of (i, k) to indicate the transmission status of the management frame.

⁷The length of the data frame is larger than all the management frame.

The status of *core process* (in red triangles) indicates that the corresponding management frame is being generated.

The last status, demonstrated in the blue square at rightmost, indicates the status of the accomplishment of the *access procedure*. And the average duration for each status can be obtained as stated in Section IV-A.

C. Dimension of zone transition: embedding 3D Markov chain

With the assumption that the time of the vehicle in an arbitrary zone z follows the geometric distribution, and the probability to transit to next zone $z + 1$ equals to δ/t_z for a short time δ , while the vehicle transverses through the coverage area, the zone index of the vehicle forms another Markov chain, as demonstrated in Fig. 5. By adding the

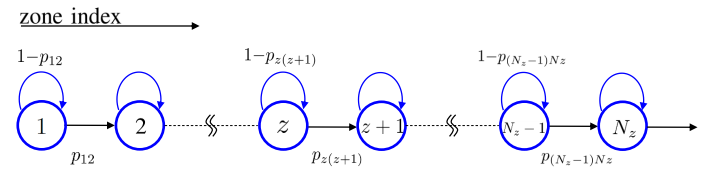


Fig. 5: Markov chain for zone transition

zone information to an arbitrary status in Fig. 4, we can describe the *access procedure* by three components: the back off stage i , the management frame index k and the zone index z , which are denoted by a vector of (i, k, z) . As the zone transition depends solely on the mobility of the vehicle, and thus is independent with the transmission of the every management frame, by sampling the beginning moment and the ending moment of each status, the vector (i, k, z) forms an embedded 3D Markov chain, which is demonstrated in Fig. 6. The 3D Markov chain includes following dimensions, which indicates the relationship with the accomplishment of the *access procedure* and the location (in which zone) of the vehicle.

1) Back off stage dimension: the index i indicates the transmission of the currently management frame is in the back off process of stage i , i.e., the back off counter C_i is a uniformly distributed variable in $[0, w * 2^i - 1]$. The status begins at the ending moment of the previous transmission attempt and ends after the transmission attempt of this back off stage. In the *core process*, the frame is under construction and has not triggered the back off process, so when k is even, the corresponding back off stage index equals to 0.

2) Management frame index dimension: when the index k is odd, it represents the transmission of $(k+1)/2$ th management frame; when the index k is even, it means the next management frame is being generated, and when k equals to $2N_A$, it means the whole *access procedure* is accomplished and the data traffic can be transmitted immediately.

3) Zone index dimension: the index z indicates the location of the vehicle, i.e., the zone where the vehicle is located at the current moment. The smaller the zone index of the vehicle when finishing the *access procedure*, the earlier the vehicle can access to Internet, i.e., the higher the throughput can be

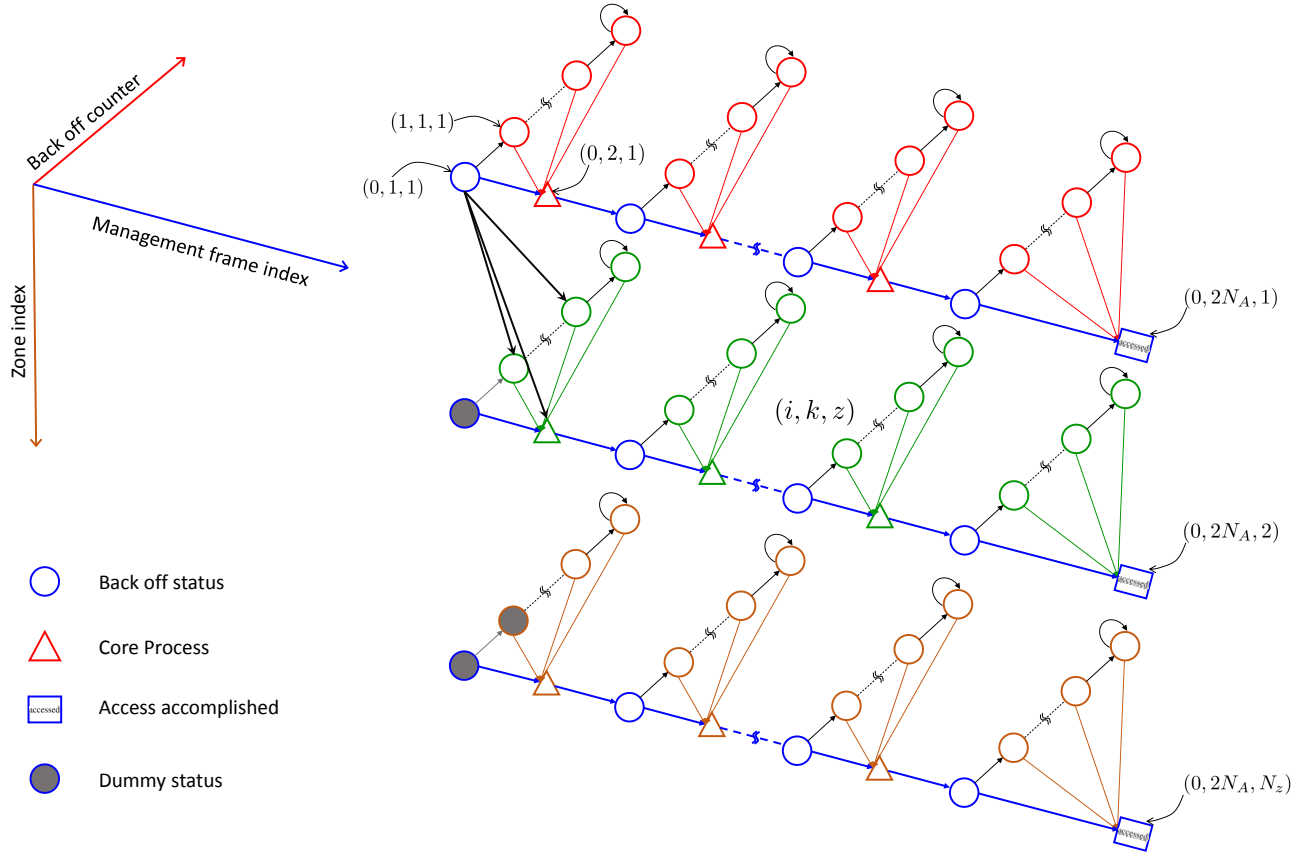


Fig. 6: 3D Markov Chain Model for *access procedure*

achieved. The zone transition can possibly happen at the end of each status and the transition probability to the next zone depends on the average sojourn duration of the current status, i.e., given a status u while the vehicle is in zone z , then the probability that the next status will be in zone $z + 1$ can be obtained by $P_u(z + 1|z) = \mathbb{E}(T_u)/t_z$.

The one step transition probability of the 3D Markov chain can be obtained as follows. For a back off status (i, k, z) in Fig. 6, the next status after a transmission attempt can have four possibilities by considering the transmission result and the zone transition. If the transmission fails due to collision or channel error, while the vehicle stays in the same zone, then the next status will be $i + 1, k, z$, or $m - 1, k, z$ if the back off stage already reach the maximum value. The one step transition probability $\mathbb{P}(i + 1, k, z|i, k, z)$ can be obtained by

$$\begin{aligned} \mathbb{P}(i + 1, k, z|i, k, z) &= P_{(b, fail, k)} \left(1 - \frac{\mathbb{E}(T_{(i, k, z)})}{t_z}\right) \\ &= P_{(b, fail, k)} \left(1 - \frac{\mathbb{E}(T_i)}{t_z}\right), \\ i \in [0, m - 2], k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z] \end{aligned} \quad (12)$$

and

$$\begin{aligned} \mathbb{P}(m - 1, k, z|m - 1, k, z) &= P_{(b, fail, k)} \left(1 - \frac{\mathbb{E}(T_{(m-1, k, z)})}{t_z}\right) \\ &= P_{(b, fail, k)} \left(1 - \frac{\mathbb{E}(T_{m-1})}{t_z}\right), \end{aligned}$$

$$k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z] \quad (13)$$

where $T_i, i \in [0, m - 1]$ is the average duration when at the back off stage i , which can be obtained via equation (3). If $z \in [1, N_z - 1]$, i.e., not the last zone, and if transmission fails and the vehicle transits to next zone, then the next status will be $(i + 1, k, z + 1)$ (or $(m - 1, k, z + 1)$ if reaches maximum back off stage), whose probability can be obtained by

$$\begin{aligned} \mathbb{P}(i + 1, k, z + 1|i, k, z) &= P_{(b, fail, k)} \frac{\mathbb{E}(T_i)}{t_z}, \\ i \in [0, m - 2], k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z - 1] \end{aligned} \quad (14)$$

and

$$\begin{aligned} \mathbb{P}(m - 1, k, z + 1|m - 1, k, z) &= P_{(b, fail, k)} \frac{\mathbb{E}(T_{(m-1, k, z)})}{t_z} \\ &= P_{(b, fail, k)} \frac{\mathbb{E}(T_{m-1})}{t_z}, \\ k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z - 1] \end{aligned} \quad (15)$$

If the transmission is successful, then the next status will be the *core process* of the next management frame or the status of 'accessed' if all management frames are transmitted, i.e., $k = 2N_A - 1$. If the vehicle continues to stay in the current zone, then the next status will be $(0, k + 1, z)$, and the one step transition probability can be obtained by

$$\mathbb{P}(0, k + 1, z|i, k, z) = (1 - P_{(b, fail, k)}) \left(1 - \frac{\mathbb{E}(t_{c, k})}{t_z}\right),$$

$$k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z] \quad (16)$$

and if the vehicle moves to next zone, then

$$\mathbb{P}(0, k+1, z+1|i, k, z) = (1 - P_{(b, fail, k)}) \frac{\mathbb{E}(t_{c, k})}{t_z},$$

$$k \text{ is odd and } \in [1, 2N_A], z \in [1, N_z - 1] \quad (17)$$

After the *core process*, the back off process is started as the management frame is ready to be transmitted. The next status will be the back off stage 0, and if the vehicle stays in current zone, the one step transition probability can be obtained by

$$\mathbb{P}(0, k+1, z|0, k, z) = (1 - P_{(b, fail, k)}) \left(1 - \frac{\mathbb{E}(t_{c, k})}{t_z}\right),$$

$$k \text{ is even and } \in [1, 2N_A - 1], z \in [1, N_z] \quad (18)$$

and if the vehicle moves to next zone, then

$$\mathbb{P}(0, k+1, z+1|0, k, z) = (1 - P_{(b, fail, k)}) \left(1 - \frac{\mathbb{E}(t_{c, k})}{t_z}\right),$$

$$k \text{ is even and } \in [1, 2N_A - 1], z \in [1, N_z - 1] \quad (19)$$

After the N_A th management frame is exchanged, i.e., the *access procedure* has been accomplished, the next status will be ‘accessed’, as the squares shown in the right side of Fig. 6. The next status depends on the zone transition, we assume that for each ‘accessed’ status, the average duration is set to a relatively small value, which is denoted by $T_{(accessed)}$. And the one step transition probability can be obtained by

$$\mathbb{P}(0, 2N_A, z|0, 2N_A, z) = 1 - \frac{\mathbb{E}(T_{(accessed)})}{t_z},$$

$$z \in [1, N_z] \quad (20)$$

and

$$\mathbb{P}(0, 2N_A, z+1|0, 2N_A, z) = \frac{\mathbb{E}(T_{(accessed)})}{t_z},$$

$$z \in [1, N_z - 1] \quad (21)$$

When transmitting the first management frame, if the vehicle transits to the next zone after a transmission attempt, it will never enter back to the previous back off stage, i.e., the vehicle will not enter into the status of $(0, 1, 1)$, whose limiting probability equals to zero, which is defined as *dummy status*. Similarly, status of $(0, 1, 2)$, $(1, 1, 2)$, $(2, 1, 3)$, etc. are also *dummy status*. And hence, the number of overall status N_s is

$$N_s = \begin{cases} N_z(mN_A + N_A) - \frac{m}{2}(m-1), & m < z \\ N_z(mN_A + N_A) - \frac{z}{2}(z-1), & m \geq z \end{cases} \quad (22)$$

Assuming that as soon as the vehicle drives out of the WiFi network, it enters an identical WiFi coverage area and performs the *access procedure* again. Based on such renewal process, the expectation of the throughput of the drive-thru Internet can be obtained by letting the vehicle re-enters the same area infinitely and calculate the average value. Thus, for all status in the last zone in Fig. 6, i.e., $z = N_z$, the one step probability can be obtained by

$$\mathbb{P}(0, 1, 1|i, k, N_z) = \frac{\mathbb{E}(T_{(accessed)})}{t_z},$$

$$i \in [0, m-1], k \in [1, 2N_A], \quad (23)$$

Denote the limiting probability of an arbitrary status (i, k, z) by $\gamma_{i, k, z}$, i.e., the stable probability that the vehicle is transmitting the k th management frame at back off stage i and located in zone z . Given the one step transition probabilities Matrix, denoted by \mathcal{M} , formed by equation (12) - (23), together with the following uniform condition for the 3D Markov chain, the limiting probability vector γ can be obtained by

$$\begin{cases} \gamma \mathcal{M} = \gamma \\ \gamma e^T = 1 \end{cases} \quad (24)$$

The probability that the vehicle is located in a certain zone \mathcal{Z} can be calculated by

$$P(\text{in Zone } \mathcal{Z}) = \sum_{z \in \mathcal{Z}} \gamma_{i, k, z} \quad (25)$$

Given the vehicle is in zone \mathcal{Z} , the conditional probability that the *access procedure* is accomplished can be calculated by

$$P(\text{accessed}|\text{in Zone } \mathcal{Z}) = \frac{\gamma_{0, 2N_A, \mathcal{Z}}}{P(\text{in Zone } \mathcal{Z})} \quad (26)$$

Denote the throughput a vehicle can achieved in zone z given the *access procedure* has been accomplished by \mathcal{U}_z , which can be obtained by

$$\mathcal{U}_z = \frac{r_z * t_z}{n+1} \quad (27)$$

where n is the number of the co-associated WiFi clients that share the bandwidth with the vehicle. And the overall throughput \mathcal{U}_T can be calculated by

$$\mathcal{U}_T = \sum_{z=1}^{N_z} \mathcal{U}_z P(\text{accessed}|\text{in Zone } z) \quad (28)$$

V. SIMULATION RESULTS

In this section, we conduct the simulation of a drive-thru Internet and compare the throughput performance with our analysis. We also discuss some potential usage of our model in future protocol design and development.

A. Simulation setup

The simulation scenario includes a WiFi AP at roadside, a tagged vehicle that repeatedly drive over the coverage area, several WiFi clients that representing the co-associated contending vehicles, which keep on transmitting the data frames to AP. The WiFi AP adopts the 802.11n (HT) protocol [25] and the data rate is determined based on the free space path loss model for each zone [37] [25], whose parameters are listed in Table II.

According to the above specifications, the zone parameters can be calculated and are listed in Table III. The link rate of the management frames are set to a constant value of 6 Mbps as observed from real access procedure, i.e., $r_k = 6$ Mbps. The link rate of the ACK frames are the same with the corresponding both management frames and data frames. The length and the *core processing* delay for the management frames

TABLE II: The WiFi parameters in simulation

Parameters	Value
DCF time slot size σ	9 μ s
SIFS size	16 μ s
DIFS size	34 μ s
PHY header duration (preamble+PLCP header)	20 μ s
Data frame length	1574 bytes
ACK frame length	32 bytes
AP radio power	18 dbm
Frequency	5.2 GHz
Noise level	-95 dbm

are measured from a real system employing the protocols of Hotspot 2.0 and WPA2-PSK similar with which in [19].

In one simulation run, the tagged vehicle will immediately perform the *access procedure* by exchanging the management set of a certain protocol, and upon its accomplishment, the vehicle start to continually transmit the data frame to the AP, and the overall data amount transmitted is record when it drives out of the coverage area, whose average value is considered to be throughput performance. And the above procedure is repeated for at least 200 runs to obtain the average throughput, which will be presented and discussed in the next Sections.

B. Simulation result

Fig. 7 shows the average aggregate throughput of the vehicle, which is obtained when the tagged vehicle can exclusively use all the link bandwidth after the *access procedure*. The maximum back off stage is set to 7 and the minimum window size is set to 16 according to the 802.11n (HT) protocol. The aggregate throughput shows the available overall throughput of the AP for the tagged vehicle’s remaining journey after the *access procedure*. It can be observed that aggregated throughput is not degraded severely until the management frame drop rate reach to a significant value. The aggregated throughput decreases when there are more contending clients, which leads to more collisions and result in more transmission attempts, especially when the channel condition is worse. And comparing the two access schemes, the Hotspot 2.0 protocol adopts more management frames then WPA2-PSK, and also involves the backhaul delay, and thus lead to less aggregate throughput.

As in reality, the aggregate throughput will be shared by all the associated clients, as shown in equation (27). To demonstrate the impact the *access procedure*, the ‘throughput loss’ is defined to evaluate the difference of the throughput that can be achieved between the case of employing and not

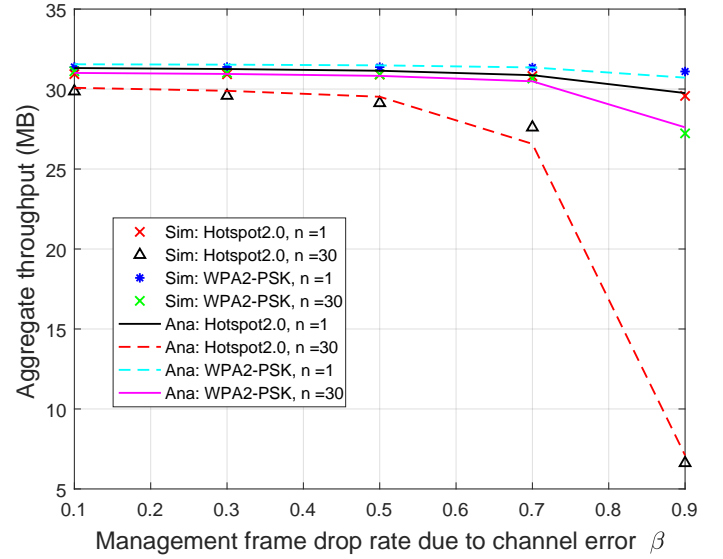


Fig. 7: Aggregate throughput vs management frame channel error rate

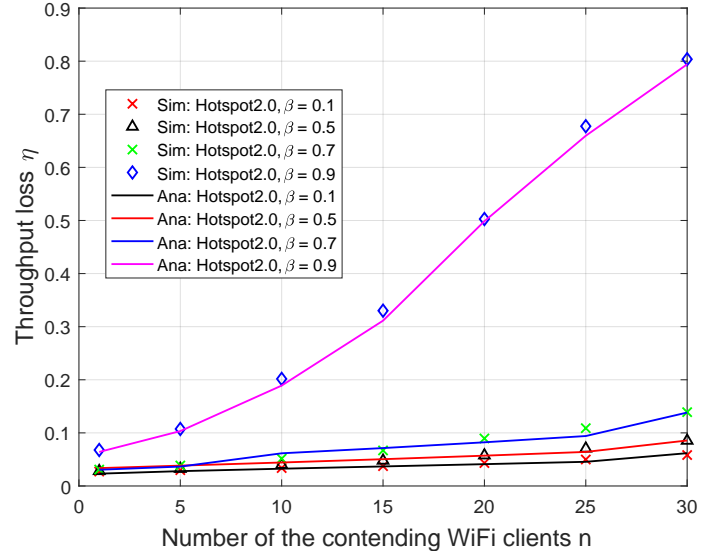


Fig. 8: Throughput loss of the tagged vehicle with Hotspot 2.0

employing *access procedure*, which is denoted by η .

$$\eta = \frac{\mathcal{U}_{total} - \mathcal{U}_T}{\mathcal{U}_{total}} \quad (29)$$

where $\mathcal{U}_{total} = \sum_{z=1}^{N_z} \mathcal{U}_z$, which is the total throughput that the tagged vehicle can achieve without the *access procedure*. Fig. 8 and Fig. 9 shows the throughput loss when employing the Hotspot 2.0 and the WPA2-PSK respectively. From the two figures, it is observed that when the number of the contending clients increase, the traffic loss is significantly exacerbated, especially when the frame drop rate is high, which is consistent with the results in Fig. 7. The traffic loss will be up to 80% when the Hotspot 2.0 is adopted, which means that the vehicle can only get around 20% of the expected throughput that no *access procedure* is employed. Similarly we can see a near 14% throughput loss when adopts WPA2-PSK, which requires to exchange much less management frames and no backhaul

TABLE III: Zone parameters

Zone index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
d_z (m)	26.8	23.9	8.4	12	6	3	5	2.4	8.2	2.4	5	3	6	12	8.4	23.9	26.8
r_z (Mbps)	6.5	13	19.5	26	39	52	58.5	65	78	65	58.5	52	39	26	19.5	13	6.5
$r_z * t_z$ (Mb) $v=60$ km/h	10.4	18.7	9.8	18.7	14	9.3	17.7	9.3	38.3	9.3	17.7	9.3	14	18.7	9.8	18.7	10.4

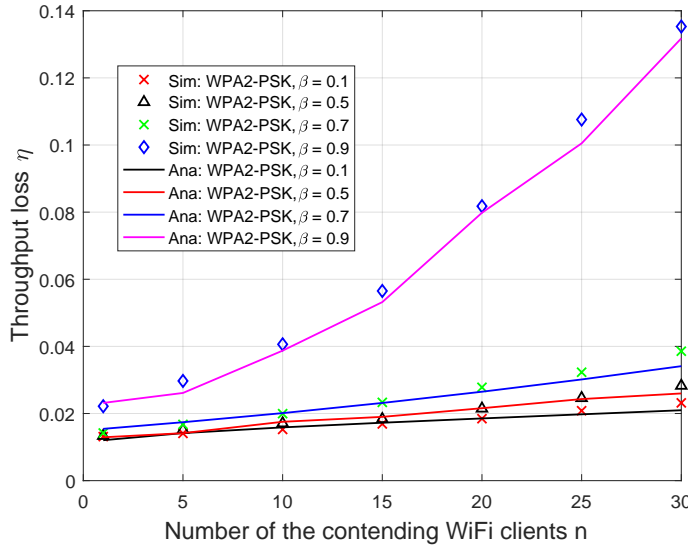


Fig. 9: Throughput loss of the tagged vehicle with WPA2-PSK

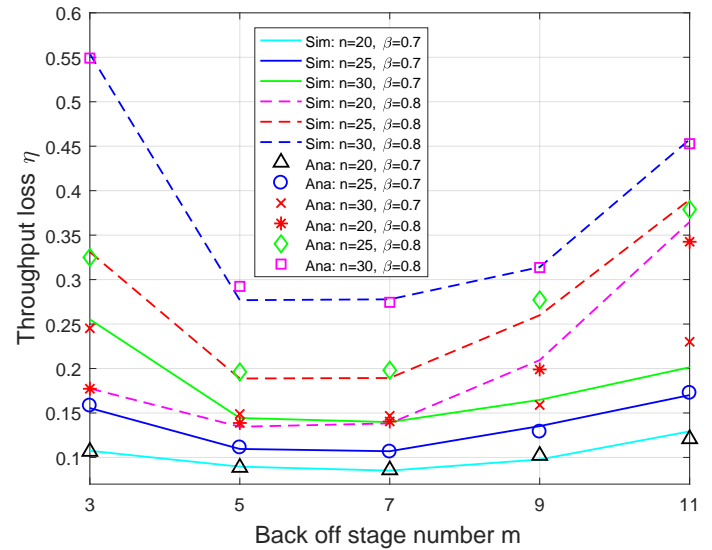


Fig. 10: Throughput loss vs. back off stage number m

handshakes.

Fig. 7-9 shows that the vehicle will lose significant throughput in the condition of large number of co-associated WiFi clients and high management frame drop rate due to channel error. Fig. 10 shows that the throughput loss is related to the back off stage number, given a certain value (16) of minimum back off window size. When the back off stage number m become small, i.e., the back off stage i in equation (5) is limited to a small value, then the average back off counter C_i is reduced, and the vehicle will have less back off waiting time before a transmission attempt, and thus lead to high collision probability, which will obstruct the *access procedure* as the management frame transmission will be delayed. And when the back off stage number become larger, the average back off counter is increased, which means that for each transmission attempt, the average waiting time will be increased, and thus the overall back off waiting time will be increased, and the average time to deliver a management frame will also be increased, and thus the *access procedure* will consume more time.

A similar observation can be found in Fig. 11, which shows the traffic loss in the condition of different values of minimum back off window size w , given a certain back off stage number (7). When w is small, the back off time for a certain back off counter is limited, and thus the management frame will be attempted to transmit shortly, which will cause high collision probability in the similar way as the case of small m , and thus the duration to transmit a management frame will be increased, and the accomplish of the *access procedure* will need more time, which increase the traffic loss. While w is too large,

the average waiting time for a given back off stage will be increased, and the average time used to transmit a management frame is thus increased, so more time will be used to finish the *access procedure*, which leads to high throughput loss as less Internet connection time will be available. Given a certain back off window parameter, it is possible to find the optimum back off stage value that minimize the traffic loss from Fig. 10. And similarly give a certain back off stage parameter, the optimum back off window value can be found via Fig. 11. And in certain conditions, it is possible to find an optimal pair of the two parameters to minimize the traffic loss introduced by the *access procedure* by exhaust all values in these two figures.

C. Potential applications

Fig. 7 - 11 have shown the accuracy of our analytical model in all aspects of conditions, which not only can be used to evaluate the throughput performance of the drive-thru Internet, but also provide potential applications for future protocol research and design in vehicular conditions, especially in V2I Internet communications.

1) *Group authentication evaluation*: Current authentication protocol requires every vehicle to perform the user authentication procedure with the roadside WiFi network, which consumes the majority of the time in *access procedure*. To reduce such overhead, a number of neighboring vehicles can form a group to perform the authentication together [38], and thus the access duration can be greatly reduces, hence the throughput loss can be greatly saved. Our model can provide a tool to calculate the network overhead of such group

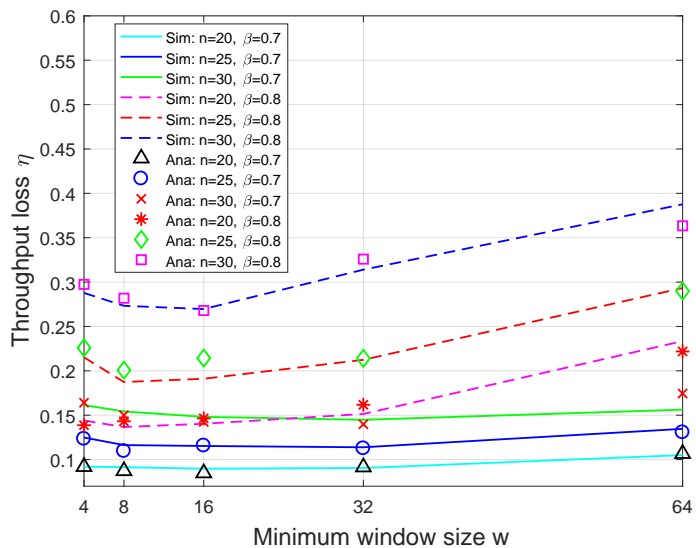


Fig. 11: Throughput loss vs. minimum window size

authentication protocols. Moreover, the trade-off between the security level of a certain authentication protocol and the corresponding throughput performance.

2) *Adaptive vehicular MAC protocol*: Fig. 10 and 11 shows that given the vehicle density and the channel condition, the throughput loss can be minimized by adjusting the MAC parameters, namely, the back off stage number and the minimum back off window size. And an adaptive MAC protocol for vehicular Internet access protocol can use our model to predict and apply the optimal values of the parameters, and thus the throughput performance can be improved [39]. Moreover, the MAC parameters can be changed to envision different service priorities for automotive WiFi clients, e.g., to provide higher throughput for users sending delay-sensitive traffic [40].

3) *Software defined vehicular networks (SDVN)*: In SDVN, a central controller can collect the global information and thus can efficiently find an optimal policy for vehicles to access Internet. Our model can be used for the controller to calculate an optimal authentication policy in different vehicular conditions, e.g., traffic density, channel quality, etc. [41].

4) *Autonomous vehicles*: Autonomous vehicles may require frequent and secure authentications to enable reliable connection for safe driving, automatic parking, etc. The network delay and exchanged messages of such process can be analyzed by our method in mobile conditions, which are crucial in future network protocol design for autonomous vehicles [42].

VI. CONCLUSION

In this paper, we have investigated the *access procedure* for a vehicle to access to the roadside WiFi network for Internet services. We have proposed a 3D Markov chain model to calculate the throughput performance of drive-thru Internet by considering the transition of the coverage zones, management frame index and the back off process. We have conducted extensive simulations to validate the accuracy of our analytical model, which can be applied in the development of future

vehicular networks, such as group authentication, mobile MAC protocol, software defined vehicular networks and connected autonomous vehicles.

VII. ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China under Project 91638204, and Natural Sciences and Engineering Research Council (NSERC), Canada.

REFERENCES

- [1] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, 2014.
- [2] W. Xu, H. Zhou, N. Cheng, F. Lyu, W. Shi, J. Chen, and X. Shen, "Internet of vehicles in big data era," *IEEE/CAA J. Autom. Sinica*, vol. 5, no. 1, pp. 19–35, 2018.
- [3] H. A. Omar, W. Zhuang, and L. Li, "Vemac: A tdma-based mac protocol for reliable broadcast in vanets," *IEEE Trans. Mobile Comput.*, vol. 12, no. 9, pp. 1724–1736, 2013.
- [4] F. Lyu, H. Zhu, H. Zhou, W. Xu, N. Zhang, M. Li, and X. Shen, "Ss-mac: A novel time slot-sharing mac for safety messages broadcasting in vanets," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 3586–3597, 2018.
- [5] A. Meola, "How the internet of things will transform private and public transportation," <http://uk.businessinsider.com/internet-of-things-connected-transportation-2016-10>, accessed April 2, 2018.
- [6] Y. Wu, L. P. Qian, H. Mao, X. Yang, H. Zhou, and X. Shen, "Optimal power allocation and scheduling for non-orthogonal multiple access relay-assisted networks," *IEEE Trans. Mobile Comput.*, 2018.
- [7] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of dsrc and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, 2016.
- [8] H. Zhou, N. Cheng, N. Lu, L. Gui, D. Zhang, Q. Yu, F. Bai, and X. Shen, "Whitefi infostation: Engineering vehicular media streaming with geolocation database," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 8, pp. 2260–2274, 2016.
- [9] Y. Wu, L. P. Qian, J. Zheng, H. Zhou, and X. Shen, "Green-oriented traffic offloading through dual connectivity in future heterogeneous small cell networks," *IEEE Commun. Mag.*, vol. 56, no. 5, pp. 140–147, 2018.
- [10] A. K. Ligo, J. M. Peha, P. Ferreira, and J. Barros, "Throughput and economics of dsrc-based internet of vehicles," *IEEE Access*, vol. 6, pp. 7276–7290, 2018.
- [11] P. Luo, Z. Ghassemlooy, H. Le Minh, E. Bentley, A. Burton, and X. Tang, "Performance analysis of a car-to-car visible light communication system," *Applied Optics*, vol. 54, no. 7, pp. 1696–1706, 2015.
- [12] Cisco, "The zettabyte era: Trends and analysis," <https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.pdf>, accessed April 2, 2018.
- [13] E. H. Ong, J. Knecht, O. Alanen, Z. Chang, T. Huovinen, and T. Nihtilä, "IEEE 802.11 ac: Enhancements for very high throughput w lans," in *2011 IEEE 22nd international symposium on Personal indoor and mobile radio communications (PIMRC)*, 2011, pp. 849–853.
- [14] W. Xu, H. Zhou, Y. Bi, N. Cheng, X. Shen, L. Thanayankizil, and F. Bai, "Exploiting hotspot-2.0 for traffic offloading in mobile networks," *IEEE Network*, to appear.
- [15] J. Ott and D. Kutscher, "Drive-thru internet: Ieee 802.11 b for" automobile" users," in *IEEE INFOCOM 2004*, vol. 1.
- [16] R. Mahajan, J. Zhorjan, and B. Zill, "Understanding wifi-based connectivity from moving vehicles," in *Proceedings of the 7th ACM SIGCOMM conference on Internet measurement*, 2007, pp. 321–326.
- [17] N. Cheng, N. Lu, N. Zhang, X. Shen, and J. W. Mark, "Opportunistic wifi offloading in vehicular environment: A queueing analysis," in *IEEE Global Communications Conference (GLOBECOM)*, 2014, pp. 211–216.
- [18] H. Zhou, B. Liu, T. H. Luan, F. Hou, L. Gui, Y. Li, Q. Yu, and X. Shen, "Chaincluster: Engineering a cooperative content distribution framework for highway vehicular communications," *IEEE transactions on intelligent transportation systems*, vol. 15, no. 6, pp. 2644–2657, 2014.

- [19] W. Xu, H. A. Omar, W. Zhuang, and X. Shen, "Delay analysis of in-vehicle internet access via on-road wifi access points," *IEEE Access*, vol. 5, pp. 2736–2746, 2017.
- [20] "Hotspot 2.0 technical task group," *Wi-Fi Alliance Technical Committee*.
- [21] L. Florio and K. Wierenga, "Eduroam, providing mobility for roaming users," in *Proceedings of the EUNIS 2005 Conference, Manchester*, 2005.
- [22] V. Bychkovsky, B. Hull, A. Miu, H. Balakrishnan, and S. Madden, "A measurement study of vehicular internet access using in situ wi-fi networks," in *Proceedings of the 12th annual international conference on Mobile computing and networking*. ACM, 2006, pp. 50–61.
- [23] N. Cheng, N. Lu, N. Zhang, X. Zhang, X. Shen, and J. W. Mark, "Opportunistic wifi offloading in vehicular environment: A game-theory approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 7, pp. 1944–1955, 2016.
- [24] T. H. Luan, X. Ling, and X. Shen, "Mac in motion: Impact of mobility on the mac of drive-thru internet," *IEEE Transactions on Mobile Computing*, vol. 11, no. 2, pp. 305–319, 2012.
- [25] "IEEE standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications," *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pp. 1–2793, 2012.
- [26] T. C. Clancy, "Secure handover in enterprise w lans: capwap, hokey, and ieee 802.11 r," *IEEE Wireless Commun.*, vol. 15, no. 5, 2008.
- [27] R. M. Lopez, A. Dutta, Y. Ohba, H. Schulzrinne, and A. F. G. Skarmeta, "Network-layer assisted mechanism to optimize authentication delay during handoff in 802.11 networks," in *Fourth Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services, MobiQuitous 2007*, pp. 1–8.
- [28] S. Shin, A. G. Forte, A. S. Rawat, and H. Schulzrinne, "Reducing mac layer handoff latency in ieee 802.11 wireless lans," in *ACM Proceedings of the second international workshop on Mobility management & wireless access protocols*, 2004, pp. 19–26.
- [29] J. Eriksson, H. Balakrishnan, and S. Madden, "Cabernet: vehicular content delivery using wifi," in *Proceedings of the 14th ACM international conference on Mobile computing and networking*, 2008, pp. 199–210.
- [30] A. Tufail, M. Fraser, A. Hammad, K. K. Hyung, and S.-W. Yoo, "An empirical study to analyze the feasibility of wifi for vanets," in *12th International Conference on Computer Supported Cooperative Work in Design*, 2008, pp. 553–558.
- [31] C.-M. Chou, C.-Y. Li, W.-M. Chien, and K.-c. Lan, "A feasibility study on vehicle-to-infrastructure communication: Wifi vs. wimax," in *10th International Conference on Mobile Data Management: Systems, Services and Middleware, MDM'09*, 2009, pp. 397–398.
- [32] W. Xu, H. Zhou, W. Shi, F. Lyu, and X. Shen, "Throughput analysis of in-vehicle internet access via on-road wifi access points," in *IEEE 86th Vehicular Technology Conference (VTC-Fall)*, 2017, pp. 1–5.
- [33] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 ghz dedicated short range communication (DSRC) frequency band," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1501–1516, 2007.
- [34] K.-H. Liu, X. Shen, R. Zhang, and L. Cai, "Performance analysis of distributed reservation protocol for uwb-based wpan," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 902–913, 2009.
- [35] P. Wang, H. Jiang, and W. Zhuang, "Capacity improvement and analysis for voice/data traffic over w lans," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1530–1541, 2007.
- [36] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, 2000.
- [37] A. Goldsmith, *Wireless communications*. Cambridge university press, 2005.
- [38] J. Ni, X. Lin, and X. Shen, "Efficient and secure service-oriented authentication supporting network slicing for 5g-enabled iot," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 644–657, 2018.
- [39] Q. Ye and W. Zhuang, "Distributed and adaptive medium access control for internet-of-things-enabled mobile networks," *IEEE Internet Things J.*, vol. 4, no. 2, pp. 446–460, 2017.
- [40] Y. Cheng, X. Ling, W. Song, L. X. Cai, W. Zhuang, and X. Shen, "A cross-layer approach for wlan voice capacity planning," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 4, pp. 678–688, 2007.
- [41] N. Zhang, S. Zhang, P. Yang, O. Alhoussein, W. Zhuang, and X. Shen, "Software defined space-air-ground integrated vehicular networks: Challenges and solutions," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 101–109, 2017.

- [42] X. Lin and X. Li, "Achieving efficient cooperative message authentication in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3339–3348, 2013.



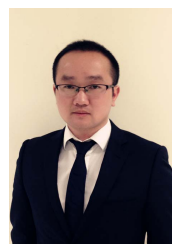
Wenchao Xu received the B.E. and M.E. degrees from Zhejiang University, Hangzhou, China, in 2008 and 2011, respectively. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. In 2011, he joined Alcatel Lucent Shanghai Bell Co. Ltd., where he was a Software Engineer for telecom virtualization. His interests include wireless communications with emphasis on resource allocation, network modeling, and mobile data offloading.



Weisen Shi received the B.S. degree from Tianjin University, Tianjin, China, in 2013 and received the M.S. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2016. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. His interests include drone communication and networking, software defined networking and vehicular networks.



Feng Lyu (IEEE M'18) received his Ph.D degree in the Department of Computer Science and Engineering from Shanghai Jiao Tong University, Shanghai, China, in 2018, and BS degree in software engineering from Central South University, Changsha, China, in 2013. Since Sept. 2018, he has been a postdoctoral fellow in BBCR Group, Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research interests include vehicular ad hoc networks, cloud/edge computing, and big data driven application design.



Haibo Zhou (M'14) received the Ph.D. degree in information and communication engineering from Shanghai Jiao Tong University, Shanghai, China, in 2014. From 2014 to 2017, he has worked a Post-Doctoral Fellow with the Broadband Communications Research Group, ECE Department, University of Waterloo. Currently, he is an Associate Professor with the School of Electronic Science and Engineering, Nanjing University. His research interests include resource management and protocol design in cognitive radio networks and

vehicular networks.



Nan Cheng (M16) received the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Waterloo in 2015, and B.E. degree and the M.S. degree from the Department of Electronics and Information Engineering, Tongji University, Shanghai, China, in 2009 and 2012, respectively. He is currently working as a Post-doctoral fellow with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada, under the supervision of Prof. Ben Liang. His current research focuses on big

data in vehicular networks and self-driving system. His research interests also include performance analysis, MAC, opportunistic communication for vehicular networks, cognitive radio, WiFi, smart grid, and cellular traffic offloading.



Xuemin (Sherman) Shen (IEEE M97-SM02-F09) received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a University Professor and the Associate Chair for Graduate Studies, Department of Electrical and Computer Engineering, University of Waterloo, Canada. Dr. Shens research focuses on resource management, wireless network security, social networks, smart grid, and vehicular ad hoc and sensor

networks. Dr. Shen served as the Technical Program Committee Chair/Co-Chair for IEEE Globecom16, Infocom14, IEEE VTC10 Fall, and Globecom07, the Symposia Chair for IEEE ICC10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC08, the General Co-Chair for ACM Mobihoc15, Chinacom07 and the Chair for IEEE Communications Society Technical Committee on Wireless Communications. He also serves/served as the Editor-in-Chief for IEEE Internet of Things Journal, IEEE Network, Peer-to-Peer Networking and Application, and IET Communications; a Founding Area Editor for IEEE Transactions on Wireless Communications; an Associate Editor for IEEE Transactions on Vehicular Technology, Computer Networks, and ACM/Wireless Networks, etc.; and the Guest Editor for IEEE JSAC, IEEE Wireless Communications, and IEEE Communications Magazine, etc. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Premiers Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada. He is a registered Professional Engineer of Ontario, Canada, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, a Royal Society of Canada Fellow, and a Distinguished Lecturer of IEEE Vehicular Technology Society and Communications Society.