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A Realistic Analytical Model for Uplink Drive-thru Internet

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***Abstract*—With the advent of various mobile Internet applications and social network services, the demand for Internet access from traveling vehicles has largely increased. In view of the ability to provide cost-effective Internet access, the Drive-thru Internet system, where road-side Access Points (APs) enable vehicular users to obtain temporary Internet connection as the vehicle passes through, is drawing dramatic attention. In this paper, we propose an analytical model to evaluate the performance of an uplink Drive-thru Internet system in the real channel conditions. The proposed analytical model accurately quantifies the performance metrics of an uplink Drive-thru Internet in terms of a number of system parameters.**

I. Introduction

Recently, there have been exponential growth of user demands in using wireless technologies to access the Internet in moving vehicles. Although people in a moving vehicle can use cellular networks such as 3G and 4G to access the Internet, the high cost and the relatively low capacity of the cellular networks largely limit the service availability. With the proliferation of public WiFi initiatives, Drive-thru Internet system has drawn considerable attention from industrial and academic fields in view of its ability to provide high data rate yet cheap Internet access via Internet Access Points (APs) widely deployed in city blocks and highways.

In a down-link Drive-thru system, the AP, as the sole message sender, transmits service messages to vehicles located within its coverage [8]. Thus, the AP is able to coordinate the down-link traffic without channel access contention. In contrast, in an uplink Drive-thru system, vehicles contend for channel access to transmit messages, such as scenic and sensory data captured along the way, to the AP based on IEEE 802.11 Distributed Coordination Function (DCF). The channel contention results in proneness to missing control messages so as to make the centralized coordination method difficult to apply to the uplink system. For time-sensitive safety applications, the dissemination latency of messages such as video clips of an accident site captured by passing vehicles is bounded by the uplink performance. Therefore, investigating the performance of uplink Drive-thru Internet system is of critical importance.

In [1], a real world measurement is conducted to test the feasibility of such Drive-Thru Internet. The result shows that a vehicle can maintain a connection to an AP for 500 m using an 802.11b hardware. Recently, several analytical models are proposed to evaluate the MAC performance of uplink Drive-thru system with moving vehicles [9], [10]. However, they only consider an ideal channel condition: a message is considered to be successfully received if and only if there is no message collision. In fact, due to multipath fading in the real environment, the signals transmitted by a vehicle may arrive at the AP with different power levels. Only if the power of a received message is higher than the power reception threshold, the message can be detected. Otherwise, the message is lost due to the propagation loss. Therefore, a message can be successfully received by the AP if and only if one of the following conditions is met: (i) a message transmitted by a vehicle is successfully detected by the AP, i.e., the received power of the message is higher than the power reception threshold, meanwhile no other vehicles transmit simultaneously; (ii) a message is successfully detected by the AP, meanwhile the messages transmitted by other vehicles are lost due to the propagation loss, i.e., the powers of the messages are lower than the power reception threshold.

In this work, we propose an analytical model to evaluate the uplink performance of a Drive-thru Internet in the real environment. A wireless propagation model is proposed to incorporate the effects of path loss and channel fading. Using the propagation model, we can derive the probability for the power of a received data to be higher than the power reception threshold. Then, the successful message reception probability can be derived based on the fact that a message transmitted by a vehicle can be successfully received by the AP if the received power is higher than the power reception threshold while the other simultaneously transmitted messages are lost. Combining it with a stochastic vehicle traffic flow model, we can derive the performance metrics of a Drive-thru Internet in a realistic setting. The accuracy of our analytical model has been validated by simulation experiment.

II. Related Works

In order to study the performance of a Drive-thru Internet, where vehicles drive through the coverage of AP, Tan *et al.* [8] propose an analytical model, which is a combination of vehicle traffic flow model and Markov reward process model. By analyzing the stochastic vehicular behaviors in terms of vehicle arrival and departure, and by mapping the data download process to a series of Markov reward process, the down-link performance metrics of Drive-thru Internet is derived. However, they only focus on down-link performance, without considering the channel access contention of DCF.

In order to capture the impact of channel access contention, the authors of [9] propose an analytical model for an uplink Drive-thru Internet. A 2-D Markov chain model is proposed, where the first dimension expresses the spatial zone in which a vehicle is currently located and the second dimension represents its backoff counter value. Using their model, the impact of vehicle speed on the network throughput can be well studied. However, they only consider the scenario in which a fixed number of vehicles are moving with constant speed. In fact, vehicle speed, density, and traffic flow interact with each other and keep changing.

In [10], an analytical model for uplink Drive-thru Internet is proposed. Using a renewal reward process model, the performance metrics of a contention-based MAC layer given a specific vehicular population within the coverage of AP is first derived. Then, the overall performance metrics are obtained by employing a stochastic traffic flow model. Nevertheless, all of these works only consider the ideal channel condition. However, the real world environmental conditions such as path loss and channel fading considerably affect the performance of wireless communications.

III. Analytical Model

In this section, we describe our analytical model. We consider a drive-thru Internet scenario, as shown in Fig. 1, which is a typical network setup along a highway or street block. An AP with a transmission range R, is placed on the road segment. Moving vehicles transmit messages to the AP while driving through its coverage. Different from previous works, realistic channel conditions, namely, path loss and channel fading, are considered in our analytical model. It is assumed that the size of messages and the data rate are constant herein.

Let d denote the vehicle density, which corresponds to the number of vehicles per unit distance along the road segment and v represents the vehicle speed, which is the distance a vehicle travels per unit time. Based on the fundamental traffic flow law [11], we have

$$d = \frac{\lambda}{v}, \tag{1}$$

where λ is the arrival rate, which corresponds to the number of vehicles that arrive at the leading edge of the coverage range of the AP per unit time. In [12], a speed-flow-density diagram is constructed, as shown in Fig. 2. Note that the vehicle flow refers to vehicle arrival rate. We can see from the figure that the traffic flow is zero, i.e., $\lambda = 0$, at two extreme points: when there are no vehicles on the road, i.e., $d = 0$, and when the vehicle density reaches the jam density so that all vehicles stop. Between these two points, a linear relationship between speed and density can be derived by

$$v = v_f(1 - d/d_{jam}), \tag{2}$$

where v_f is the free-flow speed, which corresponds to the speed of a vehicle traveling alone on the road, and d_{jam} is

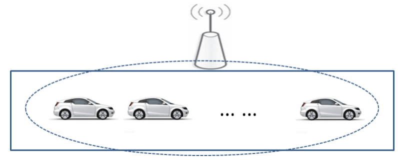

Fig. 1. Drive-thru Internet system.

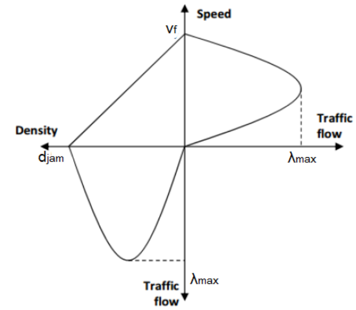

Fig. 2. Speed-flow-density diagram.

the vehicle jam density at which the traffic flow comes to a halt. The maximum number of vehicles, denoted by n_{max}, can be derived by

$$n_{max} = 2R \cdot d_{jam}. \tag{3}$$

According to [11], vehicle arrivals to the road segment can be approximated by a Poisson process with mean arrival rate λ. Thus, the inter-arrival time follows the exponential distribution with mean $1/\lambda$, from which we can deduce that the distance between two successive vehicles is also exponentially distributed with mean v/λ. Then, based on (1), the number of vehicles within AP coverage can be expressed by a random variable N, which follows a Poisson distribution with mean $2Rd$:

$$p_N(n) = \frac{e^{-2Rd} \cdot (2Rd)^n}{n! \cdot \Delta}, \tag{4}$$

where Δ is

$$\Delta = \sum_{i=1}^{2Rd_{jam}} p_N(i). \tag{5}$$

A. Transmission Failure Probability

According to the IEEE 802.11 DCF, each vehicle selects a random discrete backoff counter uniformly drawn from $[0, W_s]$ at backoff stage s, where W_s is the contention windows size of backoff stage s. If the channel is sensed idle, the vehicle decreases its backoff counter by one. The backoff counter freezes when the channel becomes busy due to transmissions from other vehicles and resumes decreasing if the channel is idle again. If the backoff counter is zero, the vehicle starts message transmission. The backoff stage s is initialized to 0 for each message and incremented by 1 after each transmission failure. If the number of retransmissions reaches the maximum retransmission limit, the message will be discarded and s will be reset to 0 for the next message. Also, once the transmission is successful, s will be reset to 0.

We divide the channel time into discrete generic time slots, each of which has distinct length. The length of each time slot is dependent on the specific channel status, namely, idle channel, failure and successful message transmissions. In IEEE 802.11 DCF, each vehicle regenerates channel access procedure for a new message after a message release, i.e., successful message transmission or message drop. Hence, with respect to an individual vehicle, the time period between two consecutive message releases forms a renewal cycle in a renewal process [7]. Assume that there are n contending vehicles within the AP coverage. Let $U(n)$ and $V(n)$ be the number of transmission attempts of a vehicle for a specific message and the number of backoff slots during the same transmission cycle, under the condition that there are n contending vehicles. Thus, for each message release, a vehicle has to go through a cycle including $U(n) + V(n)$ slots. Treating the slots where a message is transmitted as rewards in the renewal process, in each renewal cycle, a vehicle earns $U(n)$ rewards. Therefore, the long-run rate at which a vehicle earns rewards is the probability for that vehicle to transmit a message in an arbitrary time slot, denoted by $\tau(n)$. Then, we have

$$\tau(n) = \frac{\mathrm{E}[U(n)]}{\mathrm{E}[U(n)] + \mathrm{E}[V(n)]}. \tag{6}$$

Since $U(n)$ follows a truncated geometric distribution, we have

$$\mathrm{E}[U(n)] = \sum_{i=1}^{\hat{h}-1} i \cdot p_{fail}(n)^{i-1} \cdot \left[1 - p_{fail}(n)\right] + \hat{h} \cdot p_{fail}(n)^{\hat{h}-1}, \tag{7}$$

where $p_{fail}(n)$ is the probability for a message transmitted by a vehicle to fail to be received by the AP, h and $\hat{h}$ stand for the maximum backoff stage and the retry limit, respectively. The average backoff counter at backoff stage s is $W \cdot 2^{s-1}/2$, where W is the initial contention window size. Since the backoff counter freezes while the channel is sensed busy, the average number of time slots experienced at stage s is

$$B_s = \frac{W \cdot 2^{s-1}}{2 \cdot (1 - p_{tran}(n))}, \tag{8}$$

where $p_{tran}(n)$ is the probability that at least one other vehicle transmits, which can be derived by

$$p_{tran}(n) = 1 - (1 - \tau(n))^{n-1}. \tag{9}$$

Therefore, we can derive $\mathrm{E}[V(n)]$ as follows:

$$\begin{aligned}\mathrm{E}[V(n)] = &\sum_{i=1}^{h} p_{fail}(n)^{i-1}(1 - P_{fail}(n)) \cdot \sum_{j=1}^{i} B_j \\ &+ \sum_{i=h}^{\hat{h}-1} p_{fail}(n)^{i}(1 - P_{fail}(n)) \cdot \left[\sum_{j=1}^{h} B_j \right. \\ &\left. + (i - h + 1)B_h\right] + p_{fail}(n)^{\hat{h}} \cdot \left[\sum_{j=1}^{h} B_j \right. \\ &\left. + (\hat{h} - h)B_h\right]. \end{aligned} \tag{10}$$

Now we attempt to derive $p_{fail}(n)$. We consider the realistic channel conditions including large-scale path loss and small-scale channel fading. Large-scale path loss or path loss is used for predicting the mean signal strength at a particular distance from a sender, while the small-scale fading generally involves the detailed modeling of multi-path fading statistics, power delay profile, and the Doppler spectrum. We use $p_r(d)$ to denote the probability for the AP to successfully detect a message transmitted by a vehicle at a distance d. Then, $p_r(d)$ can be expressed by

$$p_r(d) = Prob(pow_r(d) > pow_{th}), \tag{11}$$

where $pow_r(d)$ and pow_{th} denote the received power of the message transmitted at a distance d and the power reception threshold respectively. Then, the Probability Density Function (PDF) of $pow_r(d)$ can be derived using the Nakagami fading model

$$f_{pow_r(d)}(x) = \left(\frac{m}{\Omega(d)}\right)^m \cdot \frac{x^{m-1}}{\Gamma(m)} \cdot e^{-\frac{mx}{\Omega(d)}}, \tag{12}$$

where m and $\Omega(d)$ denote the fading parameter and the average received power, respectively. Then, the corresponding Cumulative Distribution Function (CDF) is

$$F_{pow_r(d)}(x) = \left(\frac{m}{\Omega(d)}\right)^m \frac{1}{\Gamma(m)} \int_0^x u^{m-1} e^{-\frac{mu}{\Omega(d)}}\, \mathrm{d}u. \tag{13}$$

Then, we can derive $p_r(d)$ by

$$\begin{aligned} p_r(d) &= Prob(pow_r(d) > pow_{th}) \\ &= 1 - F_{pow_r(d)}(pow_{th}) \\ &= 1 - (\tfrac{m}{\Omega(d)})^m \tfrac{1}{\Gamma(m)} \textstyle\int_0^{pow_{th}} u^{m-1} e^{-\frac{mu}{\Omega(d)}}\, \mathrm{d}u. \end{aligned} \tag{14}$$

Based on the path loss model, we have:

$$\frac{\Omega(d_0)}{\Omega(d_1)} = \left(\frac{d_1}{d_0}\right)^{\gamma}, \tag{15}$$

where $\Omega(d_0)$ and $\Omega(d_1)$ are the mean received power of a message transmitted at a distance d_0 and d_1, respectively; γ is the path loss exponent. Since the AP should be able to detect a message's signal at a distance equal to its range R, we have

$$\frac{pow_{th}}{\Omega(d)} = \left(\frac{d}{R}\right)^{\gamma}, \tag{16}$$

Thus, using (14) and (16), we have

$$p_r(d) = 1 - \frac{(md^{\gamma})^m}{\Gamma(m)} \int_0^{1/R^{\gamma}} u^{m-1} e^{-mud^{\gamma}}\, \mathrm{d}u. \tag{17}$$

Due to the randomness of vehicle positions within the AP coverage, p_r can be derived by

$$p_r = \frac{1}{R} \int_0^R \left(1 - \frac{(md^{\gamma})^m}{\Gamma(m)} \int_0^{1/R^{\gamma}} u^{m-1} e^{-mud^{\gamma}} \mathrm{d}u\right) \mathrm{d}d. \tag{18}$$

A message can be successfully received by the AP if and only if one of the following conditions is met: (i) a message transmitted by a vehicle is successfully detected by the AP, i.e., the received power of the message is higher than the power reception threshold, meanwhile no other vehicles transmit simultaneously; (ii) a message is successfully detected by the

AP, meanwhile the messages transmitted by other vehicles are lost due to the propagation loss, i.e., the powers of the messages are lower than the power reception threshold. We denote by $p_{suc}(n)$ the probability for a vehicle to successfully transmit a message, which can be derived by

$$\begin{aligned} p_{suc}(n) &= p_r(1-\tau(n))^{n-1} + p_r \sum_{i=1}^{n-1} C_i^{n-1}\tau(n)^i \\ &\cdot (1-\tau(n))^{n-1-i} \\ &= p_r(1-\tau(n)\cdot p_r)^{n-1}. \end{aligned} \tag{19}$$

Hence, we can derive $p_{fail}(n)$ as follows:

$$p_{fail}(n) = 1 - p_{suc}(n) = 1 - p_r(1-\tau(n)\cdot p_r)^{n-1}. \tag{20}$$

The overall failure probability, conditioned only on the vehicle density, can be derived by

$$p_{fail} = \frac{\sum_{i=1}^{n_{max}} p_N(i)\cdot p_{fail}(i)}{\sum_{i=1}^{n_{max}} p_N(i)}. \tag{21}$$

B. Channel Access Delay

Since the channel access procedure of a specific vehicle regenerates itself for each message, the length of a renewal cycle equals the channel access delay. Suppose that there are n vehicles present within AP coverage. Thus, the average channel access delay, denoted by $\mathrm{E}[D_a(n)]$, can be derived by

$$\mathrm{E}[D_a(n)] = (\mathrm{E}[U(n)] + \mathrm{E}[V(n)])\cdot \mathrm{E}[T_{gen}(n)], \tag{22}$$

where $T_{gen}(n)$ is the duration of a generic backoff time slot. In each backoff slot, the probability for the AP to successfully receive a message is denoted by $p_s(n)$; the probability of occurrences of failure and idle channel are denoted by $p_f(n)$ and $p_i(n)$, respectively. Then, we have

$$\begin{cases} p_s(n) = C_1^n p_r\tau(n)(1-\tau(n))^{n-1} + \sum_{i=2}^{n} C_i^n\tau(n)^i \\ \qquad \cdot (1-\tau(n))^{n-i} C_1^i p_r(1-p_r)^{i-1}, \\ p_i(n) = (1-\tau(n))^n, \\ p_f(n) = 1 - p_s(n) - p_i(n). \end{cases} \tag{23}$$

$p_s(n)$ can be simplified as

$$p_s(n) = np_r\tau(n)(1-\tau(n)\cdot p_r)^{n-1}. \tag{24}$$

Let T_s, T_f, and T_i denote the duration of a success, a failure, and an idle backoff slot, respectively. Then, we have

$$\begin{cases} T_s = T_m + T_{sifs} + T_{ack} + T_{difs}, \\ T_f = T_m + T_{difs}, \\ T_i = \delta, \end{cases} \tag{25}$$

where T_m and T_{ack} denote the time for transmitting a message and an acknowledgement message, respectively; T_{sifs}, T_{difs}, and δ denote the duration of SIFS, DIFS, and the fixed slot time δ, which is given in the IEEE 802.11 standard, respectively. Then, $\mathrm{E}[T_{gen}(n)]$, can be derived by

$$\mathrm{E}[T_{gen}(n)] = p_s(n)\cdot T_s + p_f(n)\cdot T_f + p_i(n)\cdot \delta. \tag{26}$$

Putting all together, we can derive $\mathrm{E}[D_a(n)]$.

C. Message Throughput

Let Θ denote the nodal throughput, i.e., the throughput achieved by a vehicle. Then Θ can be derived by

$$\Theta = \frac{PS\cdot[1-(p_{fail})^{\hat{h}}]}{\mathrm{E}[D_a]}, \tag{27}$$

where PS is the payload size and $\mathrm{E}[D_a]$ is the overall channel access delay, which can be derived as follows:

$$\mathrm{E}[D_a] = \frac{\sum_{i=1}^{n_{max}} \mathrm{E}[D_a(i)]\cdot p_N(i)}{\sum_{i=1}^{n_{max}} p_N(i)}. \tag{28}$$

The overall network throughput, denoted by Φ, can be derived by analyzing at the view point of the AP. Let $\mathrm{E}[D_s(n)]$ denote the average delay that the AP successfully receives a message, given there are n vehicles. Then, we can derive $\mathrm{E}[D_s(n)]$ by

$$\mathrm{E}[D_s(n)] = \frac{\mathrm{E}[D_a(n)]}{p_s(n)}. \tag{29}$$

Thus, $\Phi(n)$, the throughput perceived by the AP, can be derived by

$$\Phi(n) = \frac{PS}{\mathrm{E}[D_s(n)]}. \tag{30}$$

Then, the overall throughput can be derived by

$$\Phi = \frac{\sum_{i=1}^{n_{max}} p_N(i)\cdot\Phi(i)}{\sum_{i=0}^{n_{max}} p_N(i)}. \tag{31}$$

Let $\mathrm{E}[\Gamma]$ denote the amount of data uploaded by a vehicle per drive-thru. The average residence time can be derived by

$$\mathrm{E}[T_{res}] = \frac{2R\cdot v_f}{1-\lambda/\lambda_{jam}}. \tag{32}$$

Then, we can derive $\mathrm{E}[\Gamma]$ as follows:

$$\mathrm{E}[\Gamma] = \Theta\cdot\mathrm{E}[T_{res}]. \tag{33}$$

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IV. Performance Evaluation

In this section, we evaluate the accuracy of our proposed analytical model using a simulation program written in MATLAB. The simulated scenario is a segment of a 1-lane, one-direction road, with an AP located at the middle point of the segment. Vehicles transmit messages to the AP based on IEEE 802.11 DCF while driving through the AP coverage. We consider the saturated message traffic case, i.e., there always exist messages for each vehicle. Simulation results are obtained by averaging over 25 runs. Table. I lists the parameters used in the simulation.

Fig. 3 shows the transmission failure probability. From the figure, it is clear that the analytical results well match the simulation curves. It can be observed that the transmission failure probability increases with vehicle density due to the reason that higher vehicle density increases the number of contending vehicles, leading to higher channel access contention. The failure probability with $R = 300m$ is higher than $R = 150m$.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Transmission power	25 dBm
Fading parameter (m)	2
Path loss exponent (γ)	2
Data rate	1 Mbps
AP transmission range (R)	150, 300 m
Vehicle density (d)	0.005-0.12 veh/m
Road segment length	1 km
Road segment direction	one-direction
Number of lanes	1
Payload size (PS)	1000 bytes
Ack message size	38 bytes
Physical layer header size	24 bytes
Initial contention window size (W)	32
Maximum backoff stage (h)	6
Retry limit ($\hat{h}$)	7
Idle backoff slot duration (T_i)	20 μs
SIFS/DIFS duration (T_{sifs}/T_{difs})	10/50 μs

This is because the larger coverage range accommodates more vehicles.

Fig. 4 shows the nodal throughput. From the figure, we can see that the throughput decreases with vehicle density. This is because higher density increases the channel access contention and transmission failure probability. Also we can see that the less AP coverage provides higher throughput. This is because less AP coverage means fewer contending vehicles.

Fig. 5 shows the amount of data uploaded by a vehicle per drive-thru. At low vehicle density, due to very low channel contention, the throughput is very high, even if the residence time is very short. When vehicle density becomes higher, the channel contention increases rapidly. Thus, the amount of data uploaded by a vehicle decreases even if it spends more time within the AP coverage. As the vehicle density further increases, the amount of uploaded data becomes increasing. This is due to the reason that when density is very large, vehicles stay a long time within AP coverage. Thus, the amount of uploaded data increases even if the channel access contention is very high.

Fig. 6 shows the overall network throughput. It can be observed from the figure that after a saturation point, the throughput starts to decrease due to excessive contention.

In order to show the impact of realistic channel conditions, the performance in realistic channel conditions is compared with ideal channel condition [10] in terms of vehicle density. In the performance comparison, the coverage range of AP is set to be 150 m.

Fig. 7 shows the comparison of transmission failure probability. From the figure, it can be discovered that the failure probability with realistic channel condition is higher. This is because with realistic channel condition, the power of a received message has to be higher than the power reception threshold in order to be successfully received by the AP even if there is no message collision. Fig. 8 shows the comparison

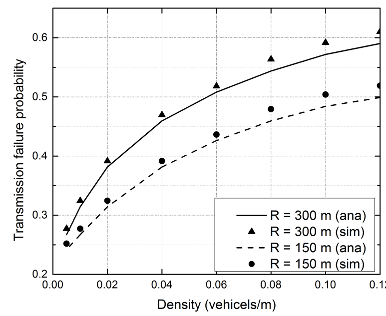

Fig. 3. Transmission failure probability.

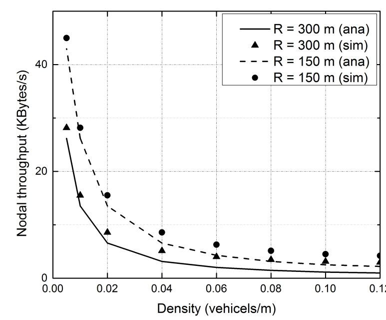

Fig. 4. Nodal throughput.

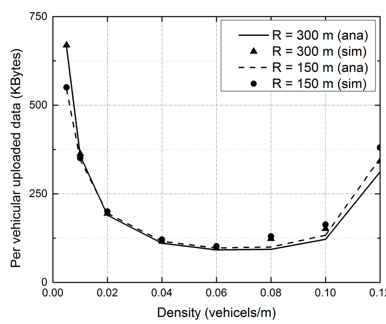

Fig. 5. Data amount uploaded by each drive-thru.

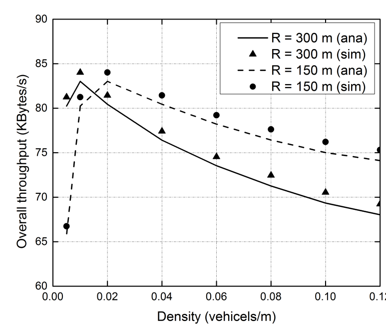

Fig. 6. Overall network throughput.

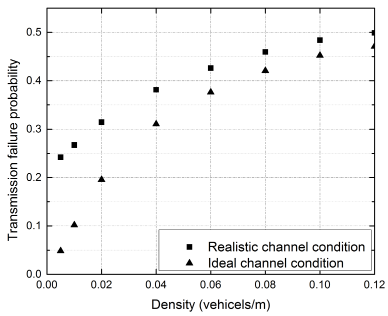

Fig. 7. Comparison of transmission failure probability.

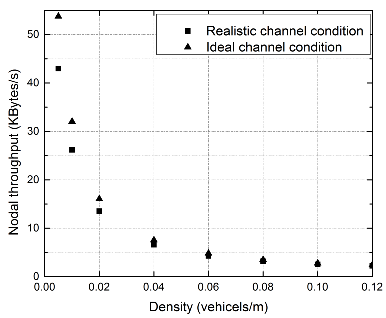

Fig. 8. Comparison of nodal throughput.

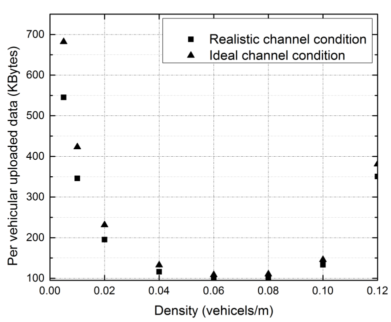

Fig. 9. Comparison of data amount uploaded per drive-thru.

of nodal throughput. We can see that the nodal throughput with realistic channel condition is lower. This occurs due to the reason that higher transmission failure probability results in more transmission attempts, thereby causing longer duration for a successful transmission. Fig. 9 shows the comparison of data amount uploaded per drive-thru. It can be observed that the throughput is lower in realistic channel case. This can be explained by the lower nodal throughput in realistic channel condition. Fig. 10 shows the comparison of overall network throughput. Also, the realistic channel condition has lower throughput due to the higher transmission failure probability.

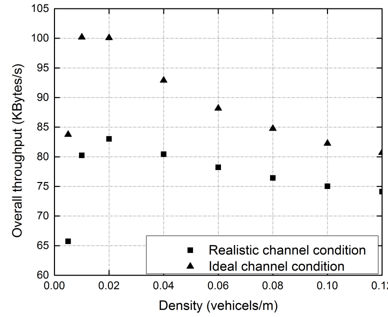

Fig. 10. Comparison of overall network throughput.

V. Conclusion

In this paper, we have developed a realistic analytical model to derive the performance metrics for a uplink Drive-thru Internet system in the realistic channel condition, considering the real channel conditions, channel access contention, and vehicle traffic flow. Our model reveals the impacts of a number of system parameters on the performance metrics. From our model, we show that the uplink throughput and transmission failure probability in the real channel conditions are lower than that in the ideal channel condition. The developed analytical model has been validated through extensive simulations.

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