Modeling and Analysis of Multichannel Drive-Thru Internet Systems and Performance Improvement

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This work was supported by the Technology Innovation Program (Development of AI-Based Autonomous Computing Modules and Demonstration of Services) funded by the Ministry of Trade, Industry and Energy (MOTIE), South Korea, under Grant 20005705.

ABSTRACT
Recently, the interest regarding Drive-thru Internet systems has been rapidly arising in industrial and academic fields in view of the widespread adoption of IEEE 802.11 networks and its great potential to provide cost-effective Internet access. Drive-thru Internet systems are multiple-access wireless networks in which users in moving vehicles request/receive services such as digital map update and MP3 download to/from a Road Side Unit (RSU) as the vehicles pass through the coverage range of the RSU. For the purpose of efficiently supporting various services, Wireless Access in Vehicular Environment (WAVE), which is the standard for VANETs communications, specifies multichannel utilization, where the overall bandwidth is subdivided into seven channels, namely, one Control Channel (CCH) and six Service Channels (SCHs). However, originally designed for quasi-static single-channel-based small-scale indoor applications, the performance of IEEE 802.11 in the outdoor vehicular environment, where a large number of fast-moving vehicles simultaneously contend for channel access in the multichannel environment, is still unclear. In this article, a unified analytical framework is established to study the performance of multichannel Drive-thru Internet systems. Specifically, taking account of channel access contention of vehicles and power reception probability of an RSU, the message arrival rate at the RSU on the uplink channel (i.e., CCH) is derived. Then, a multiserver queueing model, which plays the role of a bridge connecting the uplink and downlink (i.e., SCHs) communications, is developed for the purpose of accurately capturing the dynamics of the multichannel environment. Based on the developed framework, it can be noticed that as the intensity of channel contention increases, the saturated throughput of SCHs decreases rapidly, and the system becomes unstable due to the reason that vehicles have to wait for a very large amount of time to receive the requested service messages, or even worse, cannot receive the messages before leaving the coverage of RSU. In order to keep the throughput at the maximum level regardless of the channel contention intensity while maintaining the system stability, we propose a centralized coordination mechanism. Simulation experiments are carried out to validate the accuracy of the developed analytical framework and the effectiveness of the proposed centralized coordination mechanism.

INDEX TERMS
Performance modeling, performance analysis, Drive-thru network, IEEE 802.11 DCF, vehicular ad-hoc networks (VANETs).

I. INTRODUCTION
The past years have witnessed an exponential growth of interest regarding Vehicular Ad-hoc Networks (VANETs) in view of its crucial role in Intelligent Transportation Systems (ITS) to reduce heavy casualty tolls that are caused by vehicle crashes, and provide commercial and entertainment services that ensure comfort and efficient journeys for drivers [1]. There are two major components in VANETs: On Board Unit (OBU) and Roadside Unit (RSU) [2]. The OBU is a communication device mounted on a vehicle to operate as a mobile node. The RSU, which is an infrastructure wired to
the Internet and located at any fixed point of interest on the road, provides vehicles with Internet access. Communication between an RSU and an OBU is referred to as Vehicle-to-Infrastructure (V2I) communication, and communication among OBUs is referred to as Vehicle-to-Vehicle (V2V) communication.

For the purpose of enabling vehicular communications, the U.S. Federal Communications Commission has allocated 75 MHz of the dedicated short-range communication (DSRC) spectrum over the licensed 5.9 GHz band for vehicular networks. To enable DSRC in the 5.9 GHz band, IEEE 802.11p, which is currently integrated into the recent IEEE 802.11-2012 standard, was introduced by the Institute of Electrical and Electronics Engineers (IEEE) [3]. In the IEEE 802.11p standard, two sub-layers of the vehicular communication stack were defined: the Medium Access Control (MAC) layer and Physical layer. Furthermore, with the purpose of including the security and management planes, IEEE also introduced Wireless Access in Vehicular Environment (WAVE) standard [3]. The WAVE standard specifies the multichannel utilization, where the overall bandwidth is subdivided into seven channels, as illustrated in Fig. 2.

Channel 178 is referred to as Control Channel (CCH) and the other channels are referred to as Service Channels (SCHs). The CCH is a public channel on which a vehicle transmits a Service Request Message (SRM) for requesting a service (e.g., downloading MP3 files), while the SCHs are used to transmit the corresponding service data messages (e.g., the requested MP3 files) for serving the requested services [3].

To enable the Internet of Vehicles (IoV), it is critical to provide Internet access to vehicles on the road for the purpose of providing a wide variety of vehicular applications, such as infotainment and safety services. In light of the ability to provide cost-effective Internet access, Drive-thru Internet systems appear to be a promising solution to fulfill the data tasks. The Drive-thru Internet systems are multiple-access wireless networks allowing moving OBUs to opportunistically establish direct V2I communications with RSUs located along the road to request/receive services [5], as shown in Fig. 1. Vehicles within the coverage range of an RSU contend to upload SRMs to the RSU on the CCH based on the IEEE 802.11 Distributed Coordination Function (DCF) [6] compliant channel access contention to request services, while on the SCHs, these uploaded SRMs are served via the transfer of service messages\(^1\) of requested services from the RSU to requesting vehicles.

The Drive-thru Internet systems possess several notable advantages in providing Internet access to vehicles on the road. First, the phenomenal success of IEEE 802.11 leads

\(^1\)In this article, the terms service message and service data message are used interchangeably.
to the widespread deployment of IEEE 802.11-based RSUs (also known as APs), which have been widely used for Internet access around the world for years. In addition, compared to deploying LTE-V2X base stations [4] or consuming cellular networks, the economic cost of operating RSUs is significantly low. An RSU can be agilely set up by using commercial off-the-shelf devices with open source software, which is much cheaper than building infrastructures for LTE-V2X base stations or macro-cells [4]. Furthermore, all IEEE 802.11-based devices can work together for the reason that new transceivers are designed to be backward compatible worldwide.

The performance of a multichannel Drive-thru Internet system is affected by a number of factors, namely, the arrival rate of SRMs to the RSU on the CCH, the data transmission rate and the number of SCHs where service messages are transferred from the RSU to vehicles. Particularly, the arrival rate of SRMs is further dependent on multiple factors including the channel conditions such as path loss and channel fading, the number of contending vehicles that are concurrently present within the RSU coverage, and their residence times. Meanwhile, the number of simultaneously present vehicles depends on the vehicle density, while the residence time is dependent on the vehicle speed, which is again determined by the vehicle density. Furthermore, the data transmission rate of SCHs has a considerable impact on the service response time, i.e., the time duration needed to fulfill the service requested by an SRM. As a result, together with the multichannel access regulations, the interplay of vehicular traffic, wireless network settings and configuration has made the performance analysis of multichannel Drive-thru systems a very challenging problem.

Motivated by the above, the fundamental contributions of this article can be summarized as follows:

1) Unified analytical framework for multichannel Drive-thru Internet systems: a unified analytical framework including both up-link and down-link communications is developed. Considering channel access contention of vehicles and power reception probability of an RSU, the message arrival rate at the RSU on the uplink channel (i.e., CCH) is derived. Then, a multiserver queueing model playing the role of a bridge connecting the uplink and downlink (i.e., SCHs) communications is developed for the purpose of accurately capturing the dynamics of the multichannel environment.

2) Derivation of new performance metrics: using our framework, we derive several new performance metrics specific to multichannel Drive-thru systems: (i) service response time (i.e., the time duration needed to fulfill the service requested by an SRM, which is the sum of SRM queueing delay and requested service data message transmission time); (ii) downlink throughput (i.e., the throughput of SCHs); (iii) the average number of busy SCHs, none of which previous single-channel-based models can achieve.

3) Power reception threshold-based channel access contention model: in terms of wireless channel modeling in the context of Drive-thru systems, previous works can be classified as follows: (i) ideal channel [9]–[12], [14]–[17]; (ii) simple fixed Bit-Error-Rate (BER)-based channel [13]; (iii) Signal-to-Interference-plus-Noise-Ratio (SINR) channel [18]. Surprisingly, none of the previous works considered the power reception threshold, which is an important and fundamental component of wireless communications in Drive-thru systems. We adopt the power reception threshold model used in our previous work [5] to show its significant impact on the performance of multichannel Drive-thru systems.

4) Performance improvement: based on the developed framework, we propose a centralized coordination mechanism, which optimally determines the best initial contention window size that can maximize the downlink throughput while maintaining the system stability in terms of current vehicular traffic state. The proposed mechanism is formulated as an optimization problem, and an iterative algorithm is used to derive an accurate solution to the optimization problem.

The remainder of this article is organized as follows: In Section II, related works are introduced. Section III presents the developed analytical framework. Section IV presents the proposed centralized coordination mechanism. In Section V, the accuracy of the proposed model is validated by simulation experiments. The conclusion is provided in Section VI.

II. RELATED WORKS

A number of works have been done for analyzing the performance of static IEEE 802.11 Wireless Local Area Networks (WLANs). Bianchi [7] first analyzed DCF-based Medium Access Control (MAC) performance using a 2-D Markov-chain model and presented results in terms of bounds on achievable throughput. This model was extended to analyze more realistic performance considering all the factors specified in the IEEE 802.11 standard [8].

Different from static IEEE 802.11 networks, the special characteristics of VANETs make Drive-thru Internet systems unique in terms of some traffic features. In order to study the performance of downlink Drive-thru systems, where vehicles driving through the coverage of RSU engage in data download process, Tan et al. [9] proposed an analytical model, which is a combination of a vehicular traffic flow model and a 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 downlink performance metrics of Drive-thru Internet are derived. In [14], a reinforcement learning-based rate adjustment scheme was proposed to capture the potential channel variation patterns. In [15], the authors proposed a multidimensional Markov process-based analytical model to
Several works were conducted for analyzing DCF-contention-based uplink Drive-thru systems. In [10], Luan et al. proposed an analytical model for DCF-based uplink Drive-thru systems using a 2-D Markov chain model, where the first dimension stands for the spatial zone where a vehicle is currently located, and the second dimension represents its backoff counter value. Using their model, the impact of vehicle speed on network throughput can be well studied. This model was extended to include capture effect in [18]. In [11], Zhuang et al. proposed an analytical model by analyzing the channel access contention for each possible vehicular traffic flow separately. Then all the metrics derived in each traffic flow were summed and averaged by the number of them to obtain overall system performance. Their model is able to obtain the overall performance metrics of a last-hop Drive-thru Internet. However, their method of analyzing for every possible vehicular traffic flow separately entails a large computational complexity. In [12], the performance of Drive-thru systems was analyzed in terms of various traffic flow states and a spatial access control management scheme is proposed to improve saturated uplink throughput. In [13], in order to improve the uplink performance of Drive-thru Internet, the authors proposed a cooperative retransmission scheme, in which neighbor vehicles retransmit the overheard data frame in the previous transmission on behalf of its source vehicle, and developed a 4-D Markov chain model for evaluation. In [16], a three-dimensional Markov chain-based analytical model was proposed to investigate the throughput performance of the drive-thru internet considering the impact of the access procedure. In [17], the authors proposed a TDMA-based scheme, which can ensure the fairness of channel access. However, their TDMA-based scheme is hardly compatible with the contention-based IEEE 802.11 networks. Nevertheless, these works only dealt with the uplink performance, without considering the downlink communications.

The authors of [19] proposed an analytical model for a downlink Drive-thru system in the multichannel environment. A novel queueing model considering various behavioral characteristics is proposed to accurately quantify the performance metrics. However, their analytical model was developed on top of restrictive assumptions specific to the context of a particular scenario, where a vehicle navigating outside the coverage of any RSU remotely uploads only one SRM to the nearest possible RSU via a multihop connection, and receives the requested service data message during its residence. In general case, a vehicle can request and receive services multiple times while driving through the coverage of an RSU.
| Notation  | Description                                      |
|-----------|--------------------------------------------------|
| $d$       | Average vehicle density                         |
| $v$       | Average vehicle speed                           |
| $\lambda$ | Average vehicle arrival rate                    |
| $m$       | The number of SCHs                              |
| $W$       | Initial contention window size                  |
| $B_s$     | Average backoff counter value at backoff stage $s$|
| $p_{\text{trans}}$ | Probability of busy channel                  |
| $p_r$     | Probability of successful SRM detection         |
| $p_{\text{fail}}$ | Probability of transmission failure      |
| $\tau$   | SRM transmission probability                    |
| $T_{\text{gen}}$ | Generic slot duration                            |
| $D_a$     | Channel access delay                            |
| $I$       | Inter-arrival time of SRMs                      |
| $Y$       | Service Time of SRMs                            |
| $\lambda$ | Arrival rate of SRMs                            |
| $\mu$    | Service rate of SRMs                            |
| $D_q$     | Average queueing delay in SRQ                   |
| $\Theta_{\text{up}}$ | Per-vehicle uplink throughput              |
| $\Phi_{\text{up}}$ | Overall system uplink throughput             |
| $\Gamma_{\text{up}}$ | Average uploaded data amount per driving through |
| $\Theta_{\text{down}}$ | Per-vehicle downlink throughput               |
| $\Phi_{\text{down}}$ | Overall system downlink throughput            |
| $\Gamma_{\text{down}}$ | Average downloaded data amount per driving through |
| $ICW_{\text{opt}}$ | Optimal initial contention window size          |

Upon receiving and enqueuing an SRM into the SRQ, the RSU starts to calculate the time at which the received SRM will arrive at the Head-of-Line (HoL) position of the SRQ. This time calculation process can be handled by using the information of data transmission rate, the number of SRMs currently in the SRQ, and their service message transmission time. Then, the RSU predicts SCH availability at the instant the SRQ arrives at HoL position. If there will be more than one SCH available when the SRM reaches the HoL position, the RSU randomly chooses one among these SCHs. On the other hand, if there will be no SCH available, the RSU selects the first upcoming available SCH. Then, the information of selected SCH (e.g., its index number and the time service message transmission starts) is included in the acknowledgement message. After receiving the acknowledgement message, the requesting vehicle will switch its SCH radio (i.e., the radio which hops among SCHs) onto the announced SCH for service message reception at the indicated time.

### B. Vehicular Traffic Flow Model

Vehicular traffic flow models can be generally categorized into two major groups, namely, microscopic and macroscopic models [22]. Microscopic models consider the behavior of each individual vehicle separately, while macroscopic models integrate all the vehicles on the road into a traffic flow and describe the flow in terms of fundamental vehicular traffic parameters. In this work, we apply the macroscopic model approach to capture the effects of vehicle speed and density on vehicular population. Let $d$ and $v$ denote the average vehicle density, which corresponds to the number of vehicles per unit distance along the road segment, and the average vehicle speed, which is the distance a vehicle travels per unit time, respectively. Based on the fundamental traffic flow law [23], we have

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

where $\lambda$ is the average arrival rate, which corresponds to the number of vehicles that arrive at the leading edge of the coverage range of the RSU per unit time. In [24], a speed-flow-density diagram is constructed, as shown in Fig. 5. It can be observed from the figure that the vehicle arrival rate 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, i.e., $d = d_{\text{jam}}$, so that all vehicles stop. Between these two points, a linear relationship between speed and density can be derived by

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

where $v_f$ is the free-flow speed, which corresponds to the speed of a vehicle traveling alone on the road, and $d_{\text{jam}}$ is the
vehicle jam density at which the vehicle flow comes to a halt. According to [23], the vehicle arrivals to the road segment can be approximated by a Poisson process with mean arrival rate $\lambda$. Thus, the inter-arrival time follows an exponential distribution with mean $1/\lambda$, from which it can be deduced that the distance between two successive vehicles is also exponentially distributed with mean $v/\lambda$. Then, based on (1), $N$, the number of vehicles that are concurrently within the RSU coverage, follows a Poisson distribution. Hence, we can derive the probability of $N$ as follows:

$$\text{Prob}(N) = \frac{e^{-2Rd_s} \cdot (2Rd_s)^N}{N! \cdot \Delta}, \quad (3)$$

where $\Delta$ is

$$\Delta = \sum_{n=0}^{2Rd_{jam}} \text{Prob}(N). \quad (4)$$

$\Delta$ is used to normalize the truncated Poisson distribution given $0 \leq N \leq 2Rd_{jam}$. As a result, if one of the three vehicular traffic parameters, namely, $d$, $v$, and $\lambda$, is known, using (1)–(4), the residence time, the mean and distribution of the number of contending vehicles can be derived.

C. POWER RECEPTION THRESHOLD-BASED CHANNEL ACCESS CONTENTION MODEL

1) TRANSMISSION PROBABILITY OF SRM

Now, we attempt to derive the probability for a vehicle to transmit an SRM on the CCH. Let $\tau$ denote the transmission probability of SRM. According to the backoff procedure of DCF, in each vehicle, the backoff stage $s$ is initialized to 1 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 dropped. Each vehicle selects a random discrete backoff counter uniformly drawn from $[0, W_s]$ at backoff stage $s$, where $W_s$ is the contention window size of backoff stage $s$. The vehicle decreases its backoff counter at each idle slot $T_i$ and suspends the decrement when the channel is busy. If the channel is sensed idle again for a period of distributed interframe space (DIFS), the decrement resumes. If the backoff counter becomes zero, a vehicle attempts transmission. More details of DCF can be found in [6].

In our framework and analysis, the time of CCH is discretized into generic slots and these generic slots can be classified as follows: (i) idle slot with a time length of $T_i$ (ii) successful transmission slot with a time length of $T_s = T_{perm} + T_{sifs} + T_{ack}$, where $T_{perm}$ and $T_{ack}$ denote the time for transmitting an SRM and an acknowledgement message, respectively; $T_{sifs}$, $T_{difs}$ denote the time length of short interframe space (SIFS) and DIFS, respectively (iii) failing transmission slot with a time length of $T_f = T_s$. Each vehicle regenerates channel access procedure for a new SRM after an SRM release, i.e., successfully transmitted or dropped. Hence, for an individual vehicle, the time period between two consecutive SRM releases forms a renewal cycle in a renewal process. Let $U$ and $V$ be the number of transmission attempts of a vehicle for a specific SRM and the number of backoff slots during the same cycle, respectively. Thus, for each SRM release, a vehicle has to go through a cycle of $U + V$ generic slots. Treating the number of transmission attempts as rewards in the renewal process, in each renewal cycle, a vehicle earns $U$ rewards. Therefore, the long-run rate at which a vehicle earns rewards is the probability for that vehicle to transmit an SRM in an arbitrary generic slot. Like [9]–[12], the data traffic is supposed to be saturated, i.e., there always exists an SRM to transmit upon an SRM release in each vehicle. As a result, we have

$$\tau = \frac{E[U]}{E[U] + E[V]}. \quad (5)$$

Since $U$ follows a truncated geometric distribution, we have

$$E[U] = \sum_{i=1}^{h-1} i \cdot p_{fail}^{i-1} \cdot (1 - p_{fail}) + \hat{h} \cdot p_{fail}^{h-1}, \quad (6)$$

where $p_{fail}$ is the transmission failure probability, $h$ and $\hat{h}$ stand for the maximum backoff stage and the retransmission limit, respectively. The contention window size at backoff stage $s$ is $W_s \cdot 2^{s-1}/2$, where $W_s$ is the initial contention window size. Since the backoff counter freezes while the channel is sensed busy, the average value of the backoff counter at backoff stage $s$ is

$$B_s = \frac{W_s \cdot 2^{s-1}}{2 \cdot (1 - p_{trans})}. \quad (7)$$

where $p_{trans}$ is the probability that at least one other vehicle transmits. $p_{trans}$ can be derived by

$$p_{trans} = 1 - (1 - \tau)^{n-1}, \quad (8)$$

where $n$ denotes the average number of contending vehicles. We note that using (1)–(4), $n$ can be derived if we know one of three vehicular parameters, namely, $d$, $v$, and $\lambda$. Different from previous works that carefully track the transient movement behavior of a specific vehicle [10] or analyze the
system in terms of every possible vehicular population [11], which entails large computational complexity, our framework employs a simple yet accurate approach, where the mean vehicular population corresponding to a specific vehicular traffic parameter is directly mapped into the analytical framework. This approach is particularly applicable to statistically average performance analysis and evaluation for a Drive-thru system, as verified by the simulation experiments in Section IV.

Then, \( \text{E}[V] \) can be derived as follows:

\[
\text{E}[V] = \sum_{i=1}^{h} p_{\text{fail}}(1 - P_{\text{fail}}) \cdot \sum_{j=1}^{h} B_j + \sum_{i=h}^{h} p_{\text{fail}}(1 - P_{\text{fail}}) \cdot \left[ \sum_{j=1}^{h} B_j + (h - h)B_h \right] + p_{\text{fail}}^h \cdot \left[ \sum_{j=1}^{h} B_j + (h - h)B_h \right].
\]  

\[(9)\]

2) TRANSMISSION FAILURE PROBABILITY OF SRM

Now we attempt to derive \( P_{\text{fail}} \), considering the power reception threshold. In our framework, the channel condition includes 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 first use Nakagami fading model [25] to express the received power of a message. Then, via the path loss model, the probability that a specific received power is higher than the power reception threshold can be derived.

Let \( p_r(d) \) denote the probability for the RSU to successfully detect a message transmitted by a vehicle at a distance \( d \). Then, \( p_r(d) \) can be expressed by

\[
p_r(d) = \text{Prob}(\text{pow}_r(d) > \text{pow}_{\text{thr}}),
\]

where \( \text{pow}_r(d) \) and \( \text{pow}_{\text{thr}} \) 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 \( \text{pow}_r(d) \) can be derived using the Nakagami fading model

\[
f_{\text{pow}_r(d)}(x) = \left( \frac{\psi}{\Omega(d)} \right) x^{\psi-1} \frac{e^{-x\psi}}{\Gamma(\psi)},
\]

where \( \psi \) and \( \Omega(d) \) denote the fading parameter and the average received power, respectively; \( \Gamma(\cdot) \) is the gamma function. Then, the corresponding cumulative distribution function (CDF) is

\[
F_{\text{pow}_r(d)}(x) = \left( \frac{\psi}{\Omega(d)} \right) \frac{1}{\Gamma(\psi)} \int_0^x u^{\psi-1} e^{-\frac{\psi u}{\Omega(d)}} du.
\]

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

\[
p_r(d) = \text{Prob}(\text{pow}_r(d) > \text{pow}_{\text{thr}})
= 1 - F_{\text{pow}_r(d)}(\text{pow}_{\text{thr}})
= 1 - \left( \frac{\psi}{\Omega(d)} \right)^\psi \frac{1}{\Gamma(\psi)} \int_{\text{pow}_{\text{thr}}}^{\text{pow}_{\text{thr}}} u^{\psi-1} e^{-\frac{\psi u}{\Omega(d)}} du.
\]

Based on the path loss model, we have:

\[
\frac{\Omega(d_0)}{\Omega(d_1)} = \left( \frac{d_1}{d_0} \right)^\gamma,
\]

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; \( \gamma \) is the path loss exponent. Since the RSU should be able to detect an SRM transmitted at a distance equal to its range \( R \), we have

\[
\frac{\text{pow}_{\text{thr}}}{\Omega(d_0)} = \left( \frac{d}{R} \right)^\gamma
\]

Thus, using (13)–(15), we have

\[
p_r(d) = 1 - \left( \frac{\psi d^\gamma}{\Omega(\psi)} \right)^\psi \int_0^{1/R} u^{\psi-1} e^{-\psi u d^\gamma} du.
\]

Due to the randomness of vehicle positions within the RSU coverage, \( p_r \), the probability for the RSU to successfully detect an SRM can be derived by

\[
p_r = \frac{1}{R} \int_0^R \left( 1 - \left( \frac{\psi d^\gamma}{\Omega(\psi)} \right)^\psi \int_0^{1/R} u^{\psi-1} e^{-\psi u d^\gamma} du \right) dd.
\]

An SRM can be successfully received by the RSU if and only if one of the following conditions is met: (i) an SRM transmitted by a vehicle is successfully detected by the RSU, i.e., the received power of the SRM is higher than the power reception threshold, meanwhile no other vehicles transmit simultaneously; (ii) an SRM is successfully detected by the RSU, meanwhile the SRMs transmitted by other vehicles are lost due to the propagation loss, i.e., the power is lower than the power reception threshold. Note that the SINR model [18] cannot capture the power detection phenomenon. Under the SINR model, it is always possible for a message to be successfully received, even if its power is less than the power reception threshold, or there are more than one messages have powers higher than the power reception threshold. Therefore, \( p_{\text{suc}} \), the probability for a vehicle to successfully transmit an SRM, can be derived by

\[
p_{\text{suc}} = p_r (1 - \tau)^{n-1} + p_r \sum_{i=1}^{n-1} C_i n^{-1} \tau (1 - \tau)^{n-1-i}
\]

\[
= p_r C_i n^{-1} \tau (1 - \tau)^{n-1-i} + p_r \sum_{i=1}^{n-1} C_i n^{-1} \tau (1 - \tau)^{n-1-i}
\]

\[
= p_r \sum_{i=1}^{n-1} C_i n^{-1} \tau (1 - \tau)^{n-1-i}
\]

\[
= p_r (1 - \tau p_r)^{n-1}.
\]
Hence, we can derive $p_{\text{fail}}$ as follows:

$$p_{\text{fail}} = 1 - p_{\text{suc}} = 1 - p_r (1 - \tau p_r)^{n-1}. \quad (19)$$

Finally, putting all together, we can derive the value of $\tau$.

**D. CHANNEL ACCESS DELAY**

The channel access delay is defined as the duration from the time a vehicle starts the channel access contention on the CCH to transmit an SRM to the time the SRM is released in a vehicle. 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. Thus, the average channel access delay, denoted by $E[D_a]$, can be derived by

$$E[D_a] = (E[U] + E[V]) \cdot E[T_{\text{gen}}]. \quad (20)$$

where $E[T_{\text{gen}}]$ is the average duration of a generic slot. Let $p_r$, $p_s$, and $p_f$ denote the probability of idle slot, successful transmission slot, and failing slot, respectively. Then, we have

$$\begin{align*}
  p_s &= C^n_0 p_r \tau (1 - \tau)^{n-1} + \sum_{i=2}^{n} C^n_i \tau^i \cdot (1 - \tau)^{n-i} C^n_i (p_r (1 - p_r))^{-1}, \\
  p_f &= (1 - \tau)^n, \\
  p_f &= 1 - p_s - p_i. \\
\end{align*} \quad (21)$$

In the right-hand side of the first equation of (21), the first term stands for the event that an SRM is successfully received by the RSU if one of the contending vehicles transmits, meanwhile no other vehicles transmit at the same time; the second sum term expresses the fact that even if more than one vehicles simultaneously transmit, a successful reception is still possible if the receiving power of one SRM is higher than the power reception threshold, meanwhile the powers of others are lower than the threshold.

$p_s$ can be expressed as

$$\begin{align*}
  p_s &= p_r \cdot \tau \cdot C^n_0 \cdot \tau^0 \cdot (1 - p_r)^0 \cdot (1 - \tau)^{n-1} \\
  &+ p_r \cdot \tau \cdot C^n_2 \cdot \tau^2 \cdot (1 - p_r)^1 \cdot (1 - \tau)^{n-3} \\
  &+ p_r \cdot \tau \cdot C^n_3 \cdot \tau^3 \cdot (1 - p_r)^2 \cdot (1 - \tau)^{n-3} \\
  &\vdots \\
  &+ p_r \cdot \tau \cdot C^n_n \cdot \tau^n \cdot (1 - p_r)^{n-1} \cdot (1 - \tau)^0.
\end{align*} \quad (22)$$

We know that

$$\begin{align*}
  C^n_1 \cdot 1 &= n \cdot C^n_0 \cdot (1 - \tau)^{n-1}, \\
  C^n_2 \cdot 2 &= n \cdot C^n_1 \cdot (1 - \tau)^{n-1}, \\
  C^n_3 \cdot 3 &= n \cdot C^n_2 \cdot (1 - \tau)^{n-1}, \\
  \vdots \\
  C^n_n \cdot n &= n \cdot C^n_{n-1}.
\end{align*} \quad (23)$$

Therefore, (22) can be replaced as follows:

$$\begin{align*}
  p_s &= p_r \cdot \tau \cdot n \cdot \sum_{i=0}^{n-1} C^n_i \cdot (1 - \tau)^{n-1-i} \\
  &= p_r \cdot \tau \cdot n \cdot (1 - \tau)^{n-1}.
\end{align*} \quad (24)$$

Interestingly, from (24), it can be discovered that if multiplying the transmission probability of [11] (i.e., ideal channel condition) by the successful detection probability $p_r$, the expression for the successful transmission probability of the ideal channel condition equals to that of the power reception threshold-based channel condition.

Then, $E[T_{\text{gen}}]$ can be derived by

$$E[T_{\text{gen}}] = p_s \cdot T_s + p_f \cdot T_f + p_i \cdot T_i. \quad (25)$$

Putting all together, we can derive $E[D_a]$.  

**E. MEAN AND VARIANCE OF INTER-ARRIVAL TIME AND SERVICE TIME**

Here, the mean and variance of SRM inter-arrival time are first derived. Then, follows the derivation of the mean and variance of the service time. Herein, the SRM service time refers to the transmission time of a requested service data message.

Observe that, by looking at the system from the RSU’s perspective, a transmitted SRM is perceived as an arriving message only if it is successfully received; otherwise, the RSU will be unaware of it and not count it as an arriving message. Let $K$ denote the number of time slots elapsed before the slot at which an SRM is successfully received, and denote by $G$ the length of each of these slots. Hence, $I$, the SRM inter-arrival time can be derived as follows:

$$I = K \cdot G + T_s. \quad (26)$$

Correspondingly, the mean and variance of $I$ can be derived as follows:

$$\begin{align*}
  E[I] &= E[K \cdot G] + E[T_s], \\
  \text{Var}[I] &= \text{Var}[K \cdot G] + \text{Var}[T_s].
\end{align*} \quad (27)$$

Since the probability for an SRM to be successfully received is $p_s$, which can be derived by (24), $K$ follows a geometric distribution:

$$p_K(k) = (1 - p_s)^k \cdot p_s. \quad (28)$$

Thus, the mean and variance of $K$ can be derived by

$$\begin{align*}
  E[K] &= (1 - p_s)/p_s, \\
  \text{Var}[K] &= (1 - p_s)/p_s^2.
\end{align*} \quad (29)$$

Since $T_s$ is a constant, we have

$$\begin{align*}
  E[T_s] &= T_s, \\
  \text{Var}[T_s] &= 0. \quad (30)
\end{align*}$$
Due to the reason that before a successful SRM reception, there only exist idle and failing slots, the value of $G$ is given as follows

$$
G = \begin{cases} 
T_i, & \frac{p_i}{p_i + p_f}, \\
T_f, & \frac{p_f}{p_i + p_f}, 
\end{cases}
$$

(31)

where $p_i$ and $p_f$ can be derived by (21). Hence, the mean and variance of $G$ can be derived by

$$
\begin{align*}
E[G] &= T_i \cdot \frac{p_i}{p_i + p_f} + T_f \cdot \frac{p_f}{p_i + p_f}, \\
\text{Var}[G] &= (T_i - E[G])^2 \cdot \frac{p_i}{p_i + p_f} + (T_f - E[G])^2 \cdot \frac{p_f}{p_i + p_f}.
\end{align*}
$$

(32)

According to the well-known identities for mean and variance of random sum [26], we have

$$
\begin{align*}
E[K \cdot G] &= E[K] \cdot E[G], \\
\text{Var}[K \cdot G] &= E[K] \cdot \text{Var}[G] + \text{Var}[K] \cdot E[G]^2.
\end{align*}
$$

(33)

Finally, putting all together, we can derive the mean and variance of SRM inter-arrival time.

Let $Y$ denote the transmission time of a requested service message. Also, let $SM$ denote service message size, which is exponentially distributed as mentioned earlier. We have

$$
Y = \frac{SM}{dr},
$$

(34)

where $dr$ is the data rate. Then, the CDF of $Y$, denoted by $F_Y(y)$, is given by

$$
F_Y(y) = \text{Prob}(Y \leq y) = \text{Prob}(SM \leq y \cdot dr).
$$

(35)

Hence, the corresponding PDF of $Y$ can be derived by

$$
f_Y(y) = \frac{dF_{SM}(z)}{dz} \cdot \frac{dz}{dy} = f_{SM}(z) \cdot dr,
$$

(36)

where $z = y \cdot dr$. Since $SM$ follows an exponential distribution with mean $E[SM]$, we have

$$
f_Y(y) = \frac{1}{E[SM]} \cdot e^{-y / E[SM]} \cdot dr = \frac{dr}{E[SM]} \cdot e^{-y \cdot dr / E[SM]}.
$$

(37)

As a result, it can be concluded that $Y$ follows an exponential distribution with mean $E[SM] / dr$. Thus, the average and variance of service time can be derived as follows:

$$
\begin{align*}
E[Y] &= E[SM] / dr, \\
\text{Var}[Y] &= E[Y]^2.
\end{align*}
$$

(38)

### F. MULTISERVER QUEUEING MODEL

In this subsection, we describe the multiserver queueing model to derive the service response time, average number of busy SCHs, and uplink and downlink throughput.

1) SERVICE RESPONSE TIME AND AVERAGE BUSY SCHs

The service response time is an important QoS metric, especially for delay-sensitive applications such as safety and multimedia applications. It is the time duration elapsed from the time an SRM is successfully uploaded to the time the requested service message is completely transmitted. Hence the service response time is equal to the sum of SRM queueing delay and service message transmission times. In light of the above, the SRQ can be represented using a $G/M/m$ queueing model with infinite capacity.

An exact formula for average queueing delay can be derived by tracking all of the queue states; however, this technique entails very large computational complexity. To avoid the complexity problem, we present an approximation method. According to [27], $Q_1$, the average queue length, i.e., the average number of SRMs in the SRQ, excluding those being served on the SCHs, can be approximated by

$$
Q_1 = Q_1(M/M/m) \cdot \left(\frac{C_a^2 + C_s^2}{2}\right),
$$

(39)

where $Q_1(M/M/m)$ is the average length of an $M/M/s$ queue with the same arrival and service rate; $C_a$ and $C_s$ are the coefficient of variations for inter-arrival and service time, respectively, which can be derived by

$$
\begin{align*}
C_a &= \sqrt{\text{Var}[I] / E[I],} \\
C_s &= \sqrt{\text{Var}[Y] / E[Y].}
\end{align*}
$$

(40)

Using well-known identities for the average queue length of an $M/M/m$ queue [27], we have

$$
Q_l(M/M/m) = p_e \cdot \frac{m^m}{m!} \cdot \frac{\rho^{m+1}}{(1 - \rho)^2},
$$

(41)

where $p_e$ is the probability that the SRQ is empty. $p_e$ can be derived by

$$
p_e = \left[\sum_{i=0}^{m-1} \frac{1}{\hat{\lambda}^i \cdot \hat{\mu}^{m-i}} + \frac{m^m}{m!} \cdot \frac{\rho^m}{1 - \rho}\right]^{-1},
$$

(42)

where $\rho$ is $\hat{\lambda} / (m \cdot \hat{\mu})$; $\hat{\lambda}$ and $\hat{\mu}$ are SRM arrival rate and service rate, respectively. Hence, we have:

$$
\begin{align*}
\hat{\lambda} &= 1 / E[I], \\
\hat{\mu} &= 1 / E[Y].
\end{align*}
$$

(43)

Using Little’s law, the average queueing delay, denoted by $D_q$, can be derived as follows:

$$
D_q = \frac{Q_l}{\hat{\lambda}}.
$$

(44)

As a result, the average response time can be derived by

$$
E[D_r] = D_q + E[Y].
$$

(45)

---

2 In reality, a queue has a finite capacity of hundreds of gigabytes, which is very large compared to the size of an individual message. Hence, for simplification and tractability, it is assumed that the RSU queue has infinite capacity.
\( N_b \), the average number of busy SCHs, can be easily derived using Little’s law:
\[
N_b = \frac{\bar{\lambda}}{\mu}.
\] (46)

2) UPLINK THROUGHPUT
Per-vehicle uplink throughput \( \Theta_{ap} \) is the average SRM throughput achievable by each vehicle. Since the average duration for a vehicle to release an SRM is \( E[D_u] \), we can derive \( \Theta_{ap} \) by
\[
\Theta_{ap} = \frac{PL_{srn} \cdot [1 - (p_{fail})^\frac{1}{\mu}]}{E[D_u]},
\] (47)

where \( PL_{srn} \) is the payload size of an SRM.

Network uplink throughput, denoted by \( \Phi_{up} \), is the overall system throughput of SRM. \( \Phi_{up} \) can be derived by analyzing the SRM throughput at the viewpoint of the RSU. Since the probability for the RSU to successfully receive an SRM is \( p_s \), the average number of generic slots elapsed until a successful reception is \( 1/p_s \). Let \( E[D_u] \) denote the average duration for the RSU to successfully receive an SRM. Then, we can derive \( E[D_u] \) by
\[
E[D_u] = \frac{E[T_{gen}]}{p_s}.
\] (48)

Thus, \( \Phi_{up} \) can be derived by
\[
\Phi_{up} = \frac{PL_{srn}}{E[D_u]},
\] (49)

Let \( \Gamma_{up} \) denote the average amount of data that can be uploaded by each vehicle at the end of residence time. The average residence time, denoted by \( E[T_{res}] \), is given by
\[
E[T_{res}] = \frac{2R}{v}.
\] (50)

Then, we can derive \( \Gamma_{up} \) as follows:
\[
\Gamma_{up} = \Theta_{up} \cdot E[T_{res}].
\] (51)

3) DOWNLINK THROUGHPUT
Let \( \Phi_{down} \) denote the network downlink throughput, which is the overall system throughput of service message. Since the average number of busy SCHs is \( \hat{\lambda}/\hat{\mu} \), we can derive \( \Phi_{down} \) as follows:
\[
\Phi_{down} = \frac{\hat{\lambda}}{\hat{\mu}} \cdot d \cdot E[PL_{sm}] \cdot p_r,
\] (52)

where \( E[PL_{sm}] \) is the average payload size of service message. Then, the per-vehicle downlink throughput, \( \Theta_{down} \), can be derived by
\[
\Theta_{down} = \frac{\Phi_{down}}{n}.
\] (53)

As a result, \( \Gamma_{down} \), the average amount of service message downloadable by each vehicle per driving through, is given by
\[
\Gamma_{down} = \Theta_{down} \cdot E[T_{res}].
\] (54)

IV. CENTRALIZED COORDINATION MECHANISM
Now, we present our centralized coordination mechanism, which maximizes the service message throughput via adjusting the initial contention window (ICW) size in tune with the vehicular traffic state. Provided one of the vehicular traffic parameters, namely, vehicle density \( d \), speed \( v \), and arrival rate \( \lambda \), the optimal ICW size could be derived by solving following optimization problem:
\[
\begin{align*}
\text{maximize} & \quad \Phi_{down} \\
\text{subject to} & \quad ICW \geq 0, \\
& \quad \hat{\lambda} \cdot \frac{P_{fail}}{\hat{\mu}} \leq m - \eta.
\end{align*}
\] (55)

The second constraint in (55) is to guarantee the stability of SRQ. Since \( \hat{\lambda}/\hat{\mu} \) stands for the average number of busy SCHs, it cannot be larger than the total number of SCHs, \( m \). Otherwise, the SRQ will be unstable and overflowing with SRMs so that the service response time will be infinite. We let \( \eta = 0.01 \) herein.

Now we provide algorithms to solve the optimization problem. With some substitutions and simplifications in (52), we have
\[
\Phi_{down} = \hat{\lambda} \cdot E[PL_{sm}] \cdot p_r.
\] (56)

Hence, it is obvious that in order to maximize \( \Phi_{down} \), \( \hat{\lambda} \) should be maximized. Further, from (43), it is obvious if in order to achieve this goal, we need to minimize \( E[I] \).

From (27), \( E[I] \) can be expressed by
\[
E[I] = \frac{T_f}{np_r \cdot d \cdot \tau (1 - \tau) (1 - \tau)^n - \tau^n}.
\] (57)

In order to minimize \( E[I] \), taking derivative of (57) with respect to \( \tau \), and equating it to 0, after some simplifications, we derive (58), as shown at the bottom of the next page, where \( Q = \tau \cdot p_r \). A fixed-point iteration algorithm is utilized to obtain the value of \( Q \) in (58). The pseudo-code is outlined in Algorithm 1.

Algorithm 1 Derivation of \( Q \)

```python
//Initialization
Q = \infty
Q_{new} = 0
\epsilon = 0.000001

while abs(Q_{new} - Q) > \epsilon do

Q = Q_{new}

Use Equation (58) to calculate Q_{new}

end while
```

Then, we can derive the optimal transmission probability \( \tau_{opt} \), i.e., \( \tau_{opt} = Q/p_r \). From (5) we can express the ICW as (59), as shown at the bottom of the next page. In (8) and (19), setting the value of \( \tau \) as \( \tau_{opt} \), the values of \( P_{trans_{opt}} \) and \( P_{fail_{opt}} \) can be derived. Then, setting the values of \( P_{trans}, P_{fail}, \)
and τ in (59) to $p_{\text{trans-opt}}, p_{\text{fail-opt}}$, and $\tau_{\text{opt}}$ respectively, the optimal ICW, $ICW_{\text{opt}}$ can be derived.

However, if the optimal $\hat{\lambda}$, i.e., $\hat{\lambda}_{\text{opt}}$, is larger than $\hat{\mu} \cdot (m - \eta)$, the system is unstable. In this case, the maximum throughput can be achieved by $\hat{\lambda}_{\text{opt}} = \hat{\mu} \cdot (m - \eta)$. Then, together with (43) and (57), we have

$$\tau = \frac{(T_i - T_f) - (1 - \tau)^n + T_f}{n \cdot p_r \cdot ((\hat{\mu} \cdot (m - \eta))^{-1} - T_i + T_f) \cdot (1 - p_r \cdot \tau)^{m - 1}}.$$  
(60)

In Algorithm 1, let $Q$ refer to $\tau$ of (60), we can derive $\tau_{\text{opt}}$. Then using (59), the $ICW_{\text{opt}}$ can be derived.

The derived optimal ICW can be announced by the RSU by inserting the information of optimal ICW size into every service message so that vehicles receiving the service messages tune their ICW sizes correspondingly. Finally, the centralized coordination mechanism is outlined in Algorithm 2.

Algorithm 2 Centralized Coordination Mechanism

**Input:** One of vehicular traffic parameters, namely, $d$, $v$, and $\lambda$

**Output:** $ICW_{\text{opt}}$

Calculating the average number of contending vehicles, using (1)–(4).

Deriving $ICW_{\text{opt}}$ using Algorithm 1, (58), and (59).

if $\hat{\lambda}_{\text{opt}} > \hat{\mu} \cdot (m - \eta)$ then

Updating $ICW_{\text{opt}}$ using Algorithm 1, (59), and (60).
end if

Inserting $ICW_{\text{opt}}$ information into each service message.

### V. PERFORMANCE EVALUATION

In this section, the accuracy of the developed analytical framework and the effectiveness of the proposed centralized coordination mechanism are validated using a simulation program written in MATLAB. The simulation program is implemented using time-driven mechanism [28], where there is a variable that records the current simulation time, which is incremented by a fixed time interval $\Delta$. In our simulation, we define $\Delta$ as an idle time slot, which is the smallest inter frame space in IEEE DCF. The simulated scenario is a segment of a 2-lane, two-direction road, with an RSU located at the middle point of the segment. The vehicular traffic parameters of the two lanes are the same. All the vehicles under the RSU coverage keep sending service request messages (i.e., SRMs) to the RSU based on the IEEE DCF during their residence times in order to request services. If the RSU successfully receives a service request message, it inserts the received message into its queue. If at least one service channel is idle, the RSU serves the service request message in the HOL position of the queue by sending the requested service message to the requesting vehicle on an available service channel. Simulation time is 200 s and the results are obtained by averaging over 35 runs. Table 2 lists the parameters used in the simulation.

![Figure 6. Transmission failure probability versus density.](image)

**FIGURE 6. Transmission failure probability versus density.**

| Parameter | Value |
|-----------|-------|
| Data rates of all channels ($dr$) | 1 Mbps |
| Number of SChs ($m$) | 6 |
| Fading parameter ($\psi$) | 2 |
| Path loss exponent ($\gamma$) | 2 |
| RSU transmission range ($R$) | 150, 300 m |
| Road segment length | 1 km |
| Road segment direction | two-direction |
| Number of lanes per direction | 1 |
| Vehicle density per lane ($d$) | 0.005-0.12 veh/m |
| Vehicle flow per lane ($\lambda$) | 500-2600 veh/h |
| Vehicle speed ($v$) | 3-24 m/s |
| Vehicle jam density per lane ($d_{jam}$) | 0.13 veh/m |
| Free-flow vehicle speed ($v_f$) | 24.59 m/s |
| Payload size of SRM $PL_{SRM}$ | 105 bytes |
| Average payload size of service message $E[PL_{SRM}]$ | 1000 bytes |
| Ack message size | 18 bytes |
| MAC layer header size | 20 bytes |
| Initial contention window size ($W$) | 32 |
| Maximum backoff stage ($h$) | 6 |
| Retransmission limit ($h$) | 7 |
| Idle slot duration ($T_i$) | 20 $\mu$s |
| SIFS/DIFS duration ($T_{sifs}/T_{dfs}$) | 10/50 $\mu$s |

Table 2. Simulation parameters.
networks. We can observe that the analytical results well match the simulation curves. It can be found that the transmission failure probability increases with density due to the reason that as the vehicle density increases, more vehicles are present within the RSU coverage, leading to higher channel access contention in the saturated data traffic condition, resulting in higher transmission failure probability. Also, larger transmission range increases the failure probability, due to more contending vehicles.

In Fig. 7, we compare the transmission failure probability derived by (19) with that of the ideal channel condition, which can be derived by setting $p_r = 1$ in (19). Note that since we assume the capacity of SRQ to be infinite, there is no blocking probability. Hence, the only factor that causes transmission failure in the ideal channel condition is the message collision. In addition, in order to verify the applicability of directly mapping the mean vehicular population into the analytical framework, we also compare our framework with Zhuang’s model [11] in terms of transmission failure probability. We note that compared to our model that significantly reduces the computational complexity by directly mapping the mean vehicular population into analytical framework, Zhuang’s model investigates the system performance for every possible vehicular population separately, after which these derived performance metrics are summed and averaged by the number of them to derive a specific overall system metric, which entails very large computational complexity. From the figure, it can be discovered that the curve of our framework is higher than the other two. This is because the negative effect of the power reception threshold-based channel conditions (i.e., the power of a received message has to be higher than the power reception threshold to be successfully received even if there is no message collision), dominates over the positive effect (i.e., a message can still be successfully received even if there occurs message collision). In addition, the analytical results of the ideal channel condition derived by our framework (i.e., which can be derived by setting $p_r = 1$ in (19)) and Zhuang’s model are more or less equal to each other, verifying the applicability of direct usage of mean vehicular population in theoretical Drive-thru system performance analysis.

Figs. 8–10 show the per-vehicle uplink throughput in terms of vehicle density, speed, and flow, respectively. We can see in all of the figures that the less RSU coverage provides higher throughput due to the reason that less RSU coverage means fewer contending vehicles on average, hence lower channel contention intensity in the saturated data traffic condition. In Fig. 8, we can see that the throughput decreases as density increases. This is because higher density increases channel access contention, thereby increasing collision probability. In Fig. 9, the throughput increases as speed increases due to the reason that according to (2), higher speed can be interpreted as lower density. In Fig. 10, the throughput decreases as flow increases for the reason that larger flow means more vehicle arrivals, which leads to higher density. Fig. 11 shows the per-vehicle downlink throughput in terms of density, derived using (53). It can be observed from the figure that the throughput decreases with density due to the reason that as density increases, the uplink throughput decreases, resulting in fewer SRMs uploaded to the SRQ by each vehicle. Consequently, the amount of downloadable service messages decreases.

Fig. 12 and Fig. 13 show the average amount of data uploaded and downloaded by each vehicle per driving through, derived by (51) and (54), respectively. In Fig. 12, at low density, the uploaded data amount is very large due to
the light channel contention, which leads to large throughput in the saturated data traffic condition. When vehicle density becomes higher, the channel contention intensity increases rapidly. Thus, the amount of data uploaded by a vehicle decreases regardless of the longer residence time. As the vehicle density further increases, the uploaded data amount increases for the reason that when density is very high, vehicles stay within the RSU coverage very long. Thus, the uploaded data amount increases even if the channel contention is very intense. Fig. 13 can be explained similarly.

Fig. 14 shows the service response time derived by (45). From the figure, it can be observed that reduced RSU coverage or vehicle density increases the service response time. This is because less RSU coverage or density decreases the channel contention intensity, so increasing the number of SRMs uploaded to SRQ, resulting in larger SRQ length, thus longer response time.

Fig. 15 shows the number of busy SCHs. From the figure, it can be observed that the number of busy SCHs decreases as vehicle density increases. This is because higher vehicle density
density increases transmission failure probability, leading to fewer SRMs uploaded to SRQ, thus less number of busy SCHs are required to fulfill these SRMs. Fig. 16 shows the optimal ICW size derived by the developed centralized coordination mechanism. It can be observed that the optimal ICW increases linearly with density.

Fig. 17 and Fig. 18 show the network uplink and downlink throughput, derived using (49) and (52), respectively. We can observe from the figures that the increase of RSU coverage and density decreases the throughput due to heavier channel access contention.

To demonstrate the performance improvement achieved via the proposed centralized coordination mechanism, we compare the performance of proposed mechanism with that of the normal one, i.e., the value of ICW is fixed to be 32, as defined in the IEEE 802.11p standard [6]. Fig. 19 shows the network downlink throughput in terms of vehicle density with RSU coverage of 300 m. It can be discovered from the figure that the throughput is kept at the highest level in all vehicle densities via our proposed centralized coordination mechanism.

VI. CONCLUSION

In this article, we have developed a unified analytical framework to quantify the performance metrics for multichannel Drive-thru Internet systems. Based on the fact that a message transmitted by a vehicle is perceived by the RSU as an arriving message only if it is successfully received, the mean and variance of message arrival rate are derived using a power reception threshold-based channel contention model. Then, together with derived mean and variance of message arrival rate, we establish using a multiserver queueing model, which plays the role of a bridge connecting the uplink (i.e., CCH) and downlink (i.e., SCHs) communications. Using our framework, we have derived several new performance metrics specific to multichannel Drive-thru systems including service response time, downlink throughput, and the average number of busy SCHs, which are important metrics service providers and network designers have to consider for properly planning and designing multichannel Drive-thru Internet systems. Based on the developed analytical framework, we have shown that the saturated downlink throughput decreases rapidly as the intensity of channel contention increases. Therefore, in order to keep the throughput at the maximum level in all vehicular traffic states, we have proposed a centralized coordination mechanism to adaptively adjust the initial contention window size in tune with current vehicular traffic state. The accuracy of the developed analytical framework and the effectiveness of the proposed centralized coordination mechanism have been validated via simulations.
For future work, we plan to further extend our framework to evaluate the QoS performance for multimedia applications in the multichannel Drive-thru Internet systems.

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