Quality of Service Enhancement for Drive-thru Internet

by

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Bachelor of Communications Engineering,
Xidian University, China, 2010

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

Master of Computer Science

in the Graduate Academic Unit of Computer Science

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This thesis is accepted by the

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THE UNIVERSITY OF NEW BRUNSWICK

October, 2014

Abstract

Drive-thru Internet is a promising technique that exploits the inter-connected roadside access points (APs) to offer Internet access. Although there have been many studies aiming to improve the performance of the drive-thru Internet system, most existing solutions cannot support multiple services (e.g., data, video, and voice) and guarantee their quality of service (QoS) requirements simultaneously. This thesis presents QoS enhancement solutions for drive-thru Internet to enhance the access performance of different applications. We firstly propose an opportunistic vehicle-to-vehicle relay protocol with adaptive modulation to address the relay selection problem of drive-thru Internet. Then, an adaptive collision avoidance with service differentiation scheme is presented to improve the overall network performance with dynamically adjusted medium access control (MAC) layer parameters and support multiple services by assigning an appropriate priority level for each specific packet. We also designed and developed a simulator for comparing and evaluating different QoS schemes in a drive-thru network environment.

Acknowledgements

I wish to gratefully acknowledge the following people for their help and support during my study at UNB.

Foremost, I would like to give the sincere gratitude to my two supervisors Dr. Wei Song and Dr. Weichang Du. They devoted a large amount of time, guiding me through the research field with great patience and detailed suggestions.

I want to thank my fellows Dizhi Zhou, Peijian Ju, Xiaojing Li, A-long Jin, and Kai Dong for discussing my questions and offering constructive advice.

I am grateful to all staffs of the Faculty of Computer Science for building such a nice environment and offering relevant resources for my study and research. I would like to thank my friends for their company and assistance in my daily life.

A special appreciation is given to committee members Professor John Dedourek, Professor Virendra Bhavsar, and Professor Donglei Du. Their comments are important for my thesis.

Last but not least, I would like to express my deep appreciation to my

parents and my little sister for their love and support. Without them, I would never have the chance to study in Canada and complete the Master's thesis.

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List of Abbreviations

3G	The third generation cellular network
ACASD	Adaptive collision avoidance with service differentiation
ACW	Adaptive contention window
AIFS	Arbitration inter-frame space
AP	Access point
AC	Application category
AWGN	Additive white Gaussian noise
BBS	Basic service set
BE	Best effort traffic
BER	Bit error rate
BK	Background traffic
BPSK	Binary phase-shift keying
CCH	Control channel
CDF	Cumulative distribution function
CSM	Constant speed model

CSMA/CA	Carrier sense multiple access/collision avoidance
CW	Contention window
DA	Normal data traffic
DCF	Distributed coordination function
DEA	Distributed enhancement algorithm
DSRC	Dedicated shor-range communication
EDCA	Enhanced distributed channel access
FCC	Federal communications commission
FTM	Fluid traffic motion
IDM	Intelligent driver model
IDM-LC	Intelligent driver model with lane-changing
LEO	Low earth orbit
MAC	Medium access control
MEO	Medium earth orbit
MI	Monitor interval
M-QAM	M-ary quadrature amplitude modulation
OCB	Outside of the context of a basic service set
ORAM	Opportunistic relay with adaptive modulation
OFDM	Orthogonal frequency division multiplexing
OI	Observation interval
PHY	Physical layer
PPP	Poissson point process
PW	Priority weight
QoS	Quality of service
RSU	Roadside Unit

SCH	Service channel
SNR	Signal to noise ratio
V2I	Vehicle to vehicle
V2V	Vehicle to infrastructure
V2X	Including both V2I and V2V
VANET	Vehicular ad-hoc network
VI	Video traffic
VO	Voice traffic
VoIP	Voice over Internet Protocol
VT	Virtual transmission time
WAVE	Wireless access in vehicular networks
WiMAX	Worldwide interoperability for microwave access

List of Symbols

B_w	Channel bandwidth (Hz)
D	Tagged vehicle
E_b/N_0	Ratio of bit energy to noise power intensity
F	Maximum backoff time
F_γ	CDF of $\overline{\gamma}_{RD}$
g_{xy}	Path-loss effect
G_P	CDF of P_{RD}
$\widetilde{G}_P$	CDF of highest transmission success probability among relays
h_{xy}	Small-scale channel fading
h_W	PDF of the backoff time of the potential relay vehicles
H_W	CDF of the backoff time of the potential relay vehicles
I_c	Probability of no collision among the relay vehicles
k	$k = \log_2 M$, where M is the constellation size of modulation
K	Number of the modulation modes
K/s	Delay time units of the direct transmission from the RSU to vehicle

K/v	Delay time units of the relay transmission to vehicle
l	Number of potential relays
L	Distance between the RSU and vehicle
M	Constellation size
M_s	Constellation size of the modulation of the RSU
M_v	Constellation size of the modulation of the vehilce
N_r	Number of potential relays
N_t	Power of additive white Gaussian noise (AWGN)
P_t	Transmit power
P_t/N_t	Transmit SNR at the RSU
P_{BPSK}	Bit error rates of BPSK
P_{QAM}	Bit error rates of M-QAM
P_{RD}	Transmission success probability from relay vehicle to destination
$\widetilde{P}_{RD}$	Average transmission success probability of the best relay
P_{suc}	Overall transmission success probability
P_{SD}	Success probability of the direct transmission
P_{SR}	Probability that a relay vehicle correctly overhears the packet
P_{xy}	Probability of correctly decoding a packet from location x to y
R	Relay vehicle
R_t	Transmission rate (bps)
s	Modulation mode of the RSU
$\overline{T}$	Average packet delay
W	Backoff time
$\overline{W}$	Mean backoff time
α	Path-loss exponent

β	Threshold of the received SNR
β_s	Threshold of the received SNR from source to destination
γ_{xy}	Signal-to-noise ratio (SNR) of the received signal
$\overline{\gamma}_{RD}$	Average received SNR from a potential relay to the destination
λ	Vehicle density
Λ	Intensity measure of these potential relays

Chapter 1

Introduction

1.1 Motivation

In recent years, there have been increasing research attention to utilize existing wireless technologies such as WiFi to provide Internet access to users in moving vehicles, which is termed as drive-thru Internet [4]. Such systems take advantage of inter-connected road-side access points (APs) to enable network access to vehicular users by temporarily connecting to an AP as the vehicle passes through the AP's coverage area [5]. However, due to the challenges of the vehicular environment, the network connectivity is short-lived and the Quality of Service (QoS) to vehicular users is not satisfactory.

There are several wireless access technologies available for vehicular communications, such as IEEE 802.11, the third generation (3G) cellular network, and the Worldwide Interoperability for Microwave Access (WiMAX). IEEE

802.11 as a mature wireless technology has been widely investigated given its advantages of high bandwidth and low cost. IEEE 802.11p [6], which is an amendment of IEEE 802.11 standard, aims to provide more efficient wireless access in a vehicular environment. However, vehicular environments are more complex than common wireless environments due to their unique features, such as constrained mobility pattern, high mobility of vehicles and fast topology changes. Because of the mobility of vehicles, the radio link between two neighbor vehicles is unreliable and the opportunity of access to a road-side AP is fleeting.

Although one primary motivation for developing vehicular communication technologies is to support safety applications, which are able to prevent accidents, this thesis focuses on developing an efficient QoS enhancement solution for drive-thru Internet. There are different QoS requirements for diverse vehicular applications from best effort to guaranteed QoS requirements.

Due to the limited time and investment, it is often not feasible for researchers to deploy a real testing environment and investigate the effects of different schemes on QoS in the drive-thru Internet. To evaluate and demonstrate the QoS performance of various schemes in the specific scenario, we also develop a simulator for the drive-thru Internet.

1.2 Research Objectives

This thesis aims to develop efficient solutions to deliver packets of different categories (e.g., data, video, and voice) with specific QoS guarantee in a vehicular environment. However, there are many challenges to deal with to achieve our goal. The vehicular environment imposes its unique characteristics on the vehicular network. Besides the unstable wireless radio, the unpredictable behavior of vehicles often makes the Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) link unavailable and unreliable. Due to the limited budget, it is not possible to deploy enough APs to cover all road segments, which results that the access to the Internet in the vehicular network is usually intermittent. If many users run different applications simultaneously, the network congestion may occur and the delay would be long. Thus, efficient QoS enhancement solutions need to be developed to guarantee the user QoS requirements in the vehicular network.

1.2.1 QoS Enhancement Solutions

As the resources in a vehicular network are often limited (e.g., a limited number of APs and a small number hops), it is challenging to support IP-based applications with QoS assurance. Some applications (e.g., voice, video) have more stringent QoS requirements compared with other applications (e.g., data). Hence, it is important to incorporate service-aware QoS enhancement strategies to satisfy the different QoS requirements of various applications.

Moreover, in a real network environment, different applications are often run simultaneously by vehicle users. Hence, the QoS schemes should also provide service differentiation (e.g., among data, video, voice) so that the traffic subject to a strict QoS requirement can be prioritized.

1.2.2 Simulator for Evaluation and Comparison

In order to evaluate the performance of the QoS enhancement schemes, we also design an appropriate simulator. Because the vehicle trace which reflects the real movement of vehicles is necessary to validate the effectiveness of the proposed schemes, a vehicle trace simulator is developed firstly. The vehicle trace simulator should be able to produce a trace file according to different vehicle mobility models given a set of parameters (e.g., road topology, vehicle density, and vehicle speed range).

Due to the specific QoS requirements of different applications, a set of QoS metrics related to the applications will also be selected when we compare the performance of the QoS enhancement solutions with others. Our simulator will simulate different QoS solutions and collect their performance with respect to the specific QoS metrics. Thus, we can observe the strength and weakness of different solutions in a variety of network scenarios.

1.3 Thesis Organization

The thesis contains seven chapters, and the remaining of the thesis is organized as follows. Chapter 2 introduces the background knowledge on vehicular networks and the related works we have reviewed. Chapter 3 introduces the proposed opportunistic vehicle relay with adaptive modulation scheme. Chapter 4 presents an algorithm which is able to change medium access control (MAC) layer parameters adaptively to improve the access performance and support multiple services simultaneously. Chapter 5 describes the design and implementation of the simulator in detail, including the specific network scenario, the overall simulator framework, and the structure of the event-driven MAC layer simulator. Chapter 6 shows the simulation results, which demonstrate the effects of the schemes proposed in Chapter 3 and Chapter 4, and the two schemes combined together. Chapter 7 gives the conclusion of this thesis and highlights the future work.

Chapter 2

Background and Related Works

This chapter describes the background knowledge associated with vehicular networks. It involves a broad range of fields including vehicular mobility models, the protocol stack of vehicular networks, and connectivity issues of vehicular networks. Besides, the related works proposed in the literature are also introduced.

2.1 Vehicular Networks

2.1.1 Vehicle Mobility

To better understand the unique features of vehicular networks and evaluate the performance of our future QoS enhancement schemes, the traffic flow model should be investigated firstly. There are two points of view for vehicular mobility modeling: macro-mobility and micro-mobility.

Macro-mobility models mainly take into account the road topology, the road structure (unidirectional or bidirectional, single- or multiple-lane), the road characteristics (speed limits) and the traffic signs. Micro-mobility models consider the movements of each individual vehicle separately. Such models mainly take into account the mobility parameters of vehicles (acceleration or decelerations rate, desired speed) and the features of drivers' behavior (car following rules, lane changing rules, politeness factor).

Let q be the vehicle flow which measures the number of vehicles that pass a fixed roadside observation point per unit time. Moreover, let λ be the vehicle density, which is the average number of vehicles per unit distance along the road segment. Let v represent the vehicle speed. These three variables are related by the following fundamental traffic flow law [1]:

$$q = \lambda v \ . \tag{2.1}$$

The typical speed-flow-density diagrams can be constructed. Fig. 2.1 shows the relationships between the speed-flow, the speed-density, and the flow-density diagram. As density λ increases from zero, flow q also increases, since more vehicles are on the road and the decline of speed is negligible at low density. As density continues to increase, speed decreases significantly because of the interaction between vehicles. The flow capacity is reached when density and speed result in the maximum flow. When density is high,

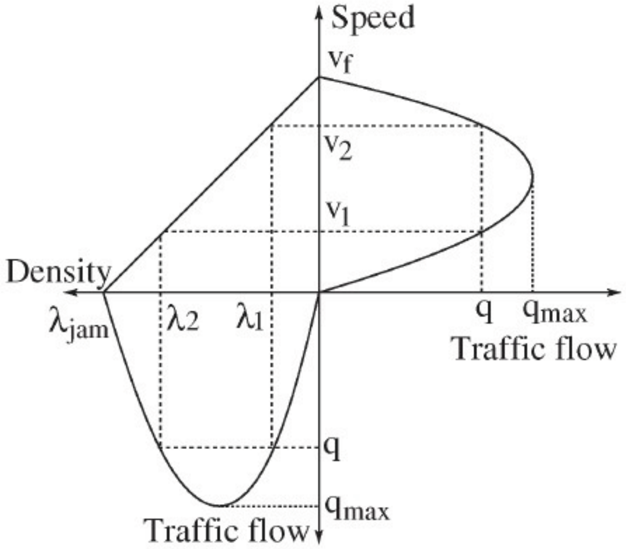


Figure 2.1: Relationships between the speed-flow, speed-density, and flow-density [1].

flow decreases because of the significant drop of speed until it reaches the jam situation.

In practice, the vehicle density cannot be unlimited due to the length of the vehicle, the road conditions and the safety rules (safety distance between adjacent vehicles). Thus, let δ_{jam} be the road capacity per unit distance, which is the minimum allowable inter-vehicle distance. So the maximum allowable traffic density λ_{jam}, or jam density, is given by

$$\lambda_{jam} = 1/\delta_{jam} \ . \tag{2.2}$$

To complete the description of the vehicular mobility model, the relationship between the vehicle speed and the other system parameters must be specified. Three major mobility models are introduced in the following.

The constant speed motion (CSM) [7] model is the simplest one and $v(t)$ determines the speed of all vehicles as follows:

$$v(t) = v_{min} + (v_{max} - v_{min}) \cdot \eta \tag{2.3}$$

where $v(t)$ is the speed of the vehicle in time t, v_{min} is the minimum allowed speed, v_{max} is the maximum allowed speed and η is a random variable uniformly distributed in [0,1].

The fluid traffic motion (FTM) [8] model captures the dependency between the speed of the vehicle and the average vehicle density as follows:

$$v(t) = max\left\{v_{min}, v_{max}\left(1 - \frac{\lambda}{\lambda_{jam}}\right)\right\} \quad . \tag{2.4}$$

According to the FTM model, when the number of vehicles increases, all vehicles slow down up to a lower bound on the speed when the vehicle density reaches the jam state.

The intelligent driver model (IDM) [9] captures the car following behavior based on live observation. The instantaneous acceleration of a vehicle is defined by

$$\frac{dv}{dt} = a_m\left[1 - \left(\frac{v}{v_0}\right)^4 - \left(\frac{s^*}{s}\right)^2\right] \quad . \tag{2.5}$$

Here, in (2.5), a_m is the maximum acceleration of the vehicle, v is the current speed of the vehicle, v_0 is the desired velocity, s is the distance from the preceding vehicle and s^* is a desired dynamical distance. The s^* is given by

$$s^* = s_0 + vT + \frac{v\Delta v}{2\sqrt{a_m b}} \tag{2.6}$$

where s_0 is the minimum desirable bumper-to-bumper distance, T is the minimum safe time between two vehicles, Δv is the speed difference with respect to the velocity of the front vehicle, and b is the normal deceleration rate.

The IDM model with lane-changing (IDM-LC) further captures the lane change behavior into the IDM model. The relationship is given by the following inequalities

$$a_l - a \pm a_{bias} > p(a_{cur} + a_{new} - a^l_{cur} - a^l_{new}) + a_{thr} \tag{2.7}$$

$$a^l_{new} > -a_{safe} \ . \tag{2.8}$$

Here, in (2.7), a_l is the acceleration of the target vehicle after lane change, a is the acceleration of the target vehicle in the current lane, a_{bias} is a lane bias factor, p is a driver politeness factor, a_{cur} is the acceleration of the following vehicle in the current lane before lane change, a_{new} is the acceleration of the following vehicle in the new lane before lane change, a^l_{cur} is the acceleration of the following vehicle in the current lane after lane change, a^l_{new} is the acceleration of the following vehicle in the new lane after lane change, a_{thr} is the overall advantage threshold below which lane change would not happen.

Thus, $(a_l - a)$ is the acceleration gain of the target vehicle after lane change, while the similar expressions $(a_{cur} - a_{cur}^l)$ and $(a_{new} - a_{new}^l)$ represent the loss in acceleration for the following vehicle in the current lane and the new lane after lane change. Besides, a_{bias} encourages lane change to a particular side. For example, because the right lane is the default lane in Canada, vehicles usually drive on the right lane except for overtaking other vehicles. The left part in (2.7) would be $(a_l - a + a_{bias})$ if the lane change from left to right is considered; otherwise, the left part would be $(a_l - a - a_{bias})$. In addition, p determines the degree that the behavior of drivers influences the lane change decisions, and a big value of p will decrease the number of lane changes. Thus, (2.7) means that a lane change will occur if the advantage of the target vehicle changing lane to a new lane is greater than the disadvantage of following vehicles in the current lane and the new lane. In (2.8), a_{safe} is the maximum possible deceleration which is a positive value. The deceleration of the following vehicle in the new lane should be above the safe limit value $-a_{safe}$. Hence, (2.8) specifies that too quick deceleration which could cause an accident is not allowable due to the consideration of safety. Only if both inequalities (2.7) and (2.8) are satisfied would the lane change happen.

The IDM-LC is more realistic compared with the CSM and FTM models. A vehicle modeled by IDM-LC is able to change acceleration or deceleration according to the behavior of neighbor vehicles. Moreover, a vehicle can change lane if it can get more advantage in the new lane. To evaluate the performance of vehicular networks, a proper realistic vehicle traffic model should be employed.

2.1.2 Protocol Stack of Vehicular Ad-hoc Networks (VANETs)

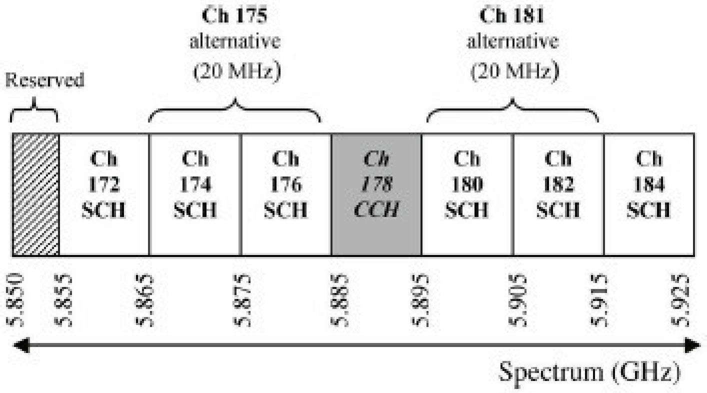


Figure 2.2: DSRC channel designations in the U.S. [2].

Dedicated short-range communications (DSRC) standard suite [2] is considered as one of the most promising Wireless Access in Vehicular Networks (WAVE) technologies in VANETs. DSRC is “Dedicated” because the U.S. Federal Communications Commission (FCC) has allocated 75 MHz of licensed spectrum in the 5.9 GHz band for DSRC communications, which is shown in Fig. 2.2. “Short Range” in DSRC means that the coverage of DSRC is hundreds of meters.

The spectrum allocated by FCC for DSRC operation in the U.S. is divided into seven 10 MHz channels with 5 MHz guard band at the low end, as illustrated in Fig. 2.2. The FCC has also designated each channel as either a Service Channel (SCH) or as a Control Channel (CCH). As we can see, there are 6 SCHs available for infotainment communications in VANETs.

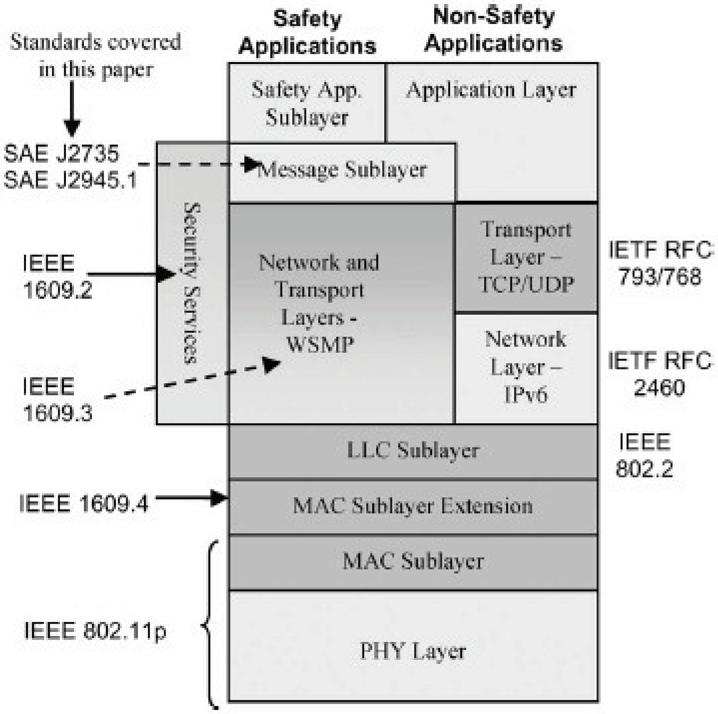


Figure 2.3: Layered architecture for DSRC in the U.S. [2].

The effectiveness of DSRC is highly dependent on the interoperability of multiple standards. Fig. 2.3 shows the layered architecture of DSRC. As seen, the protocols used in DSRC include

- IEEE 802.11p [6]: at the bottom of the stack, which defines the physical and MAC layers to support communications in vehicular environments.

- IEEE 1609.4: as a MAC sublayer extension that provides multi-channel operation.
- IEEE 1609.3: the WAVE Short Message Protocol (WSMP) provides non-routed data exchange and supports safety applications in vehicular networks.
- IEEE 1690.2: which provides security services such as message authentication and encryption.
- SAE J2735: which specifies the format of messages.
- SAE J2945.1: which describes the minimum performance requirements.

As the foundation of DSRC, IEEE 802.11p is an amendment of IEEE 802.11 standards and aims to provide wireless communications in vehicular environments.

At the physical layer (PHY), the philosophy of IEEE 802.11p design is to make the minimum necessary changes to the typical IEEE 802.11 physical layer. IEEE 802.11p utilizes the well-known orthogonal frequency division multiplexing (OFDM) technique, originally introduced in the IEEE 802.11a amendment. At the transmitter, spectral mask is defined to limit the out-of-band energy. At the receiver, channel rejection is used to filter out energy that is outside the channel.

At the MAC sublayer, like other standards of IEEE 802.11, IEEE 802.11p also uses carrier sense multiple access/collision avoidance (CSMA/CA) as the basic medium access. A key purpose of the IEEE 802.11p amendment is to enable efficient channel access in the vehicular environment without more overhead than that typically needed in the standard IEEE 802.11 MAC. The IEEE 802.11 standard defines a concept called the Basic Service Set (BSS). A BSS is a set of stations that share a common channel to exchange data information. Before a station can transmit, it must hear the BSS announcement and go through a series of “setup” steps: including joining, authenticating, and associating. In a highly mobile vehicular environment, the opportunity to communicate may be fleeting, and thus “lightweight” rules for medium access are desired. To achieve this objective, OCB (Outside the context of a BSS) communications are designed. In the traditional IEEE 802.11, stations belonging to the same BSS exchange data frames. However, in OCB communications, stations that do not belong to a BSS can also exchange data frames and do not need the MAC sublayer setup. The OCB capability is preferred for V2V safety exchanges.

2.1.3 Connectivity of VANETs

To model the connectivity in VANETs, there are some existing analytical models that differ with respect to the assumptions about the road topology, the traffic density, the vehicle speed, the vehicles distribution and mobility, the communication type and the transmission range, and the number of communication hops. The common objective of these analytical models is to find out how the network and road parameters affect the connectivity behavior in VANETs.

For V2V connectivity, the vehicle density and the radio communication range are two major factors which should be considered. There is a common assumption that the inter-vehicle distance should follow an exponential distribution, which has been shown to be in good agreement with real vehicle traces under uncongested traffic conditions [10]. Assuming that these inter-vehicle distances are exponentially distributed and that all vehicles travel in the same direction, we have the probability that two consecutive vehicles are disconnected, given by

$$P\{X > R\} = e^{-\lambda R} \tag{2.9}$$

where X is the inter-vehicle distance, λ is the parameter for the exponential distribution of X and R is the radio communication range. It is obvious that, as the vehicle density or radio communication range increases, the probability of disconnected vehicles decreases.

For V2I connectivity, there have been some preliminary field-trials to prove the feasibility of using V2I communications to support Internet-based applications, *e.g.*, in [11], [4]. Under the budget constraint, it is not feasible to cover all roads with road-side APs. In fact, with gaps between the coverage of two adjacent APs, the V2I connectivity is usually fleeting and intermittent. The experimental study in [11] shows that the median of the V2I connection duration is around 13 seconds, while the mean duration between connections is around 75 seconds. Because roadside unit (RSU) is a fixed infrastructure AP node, which is not able to change its deployment with the dynamic vehicle density, the RSUs are usually assumed to be uniformly deployed along a road. To increase the probability of access to RSUs, multi-hop communications of VANETs [12] have been proposed so that a vehicle in the gap between two APs is able to connect with an RSU via one or more relay vehicles. By using an efficient relay method, most IP-based applications can be enabled even in a sparse RSU deployment scenario. However, the number of hops is often limited (usually less than 3) for simplicity. As a result, when the vehicle density is low, the vehicle in the coverage gap may not be able to reach an RSU even using the relay of neighbor vehicles.

2.2 Related Works

Although one primary motivation of developing VANETs is to support safety applications, which are able to prevent accidents, this thesis focuses on the drive-thru Internet to support traditional IP-based applications. To satisfy the specific QoS requirements of different applications in a vehicular environment, there have been some interesting solutions proposed in the literature. To leverage the mobility of vehicles, a store-carry-and-forward approach was proposed in [13] for delay-tolerant applications. Messages that are cached in a carrying vehicle are buffered to be forwarded to the next vehicle. However, this method is only suitable for the applications that can accept a long delay and frequent link breaks.

In [14], an enhanced navigation system was implemented based on V2X (including both V2V and V2I) communications. The messages on road conditions are forwarded to vehicles periodically to help drivers circumnavigate congested roads and avoid traffic roadblocks. This is an efficient way to improve transport efficiency and the application does not require real-time but reliable message delivery.

In [15], a dedicated Low Earth Orbit (LEO) / Medium Earth Orbit (MEO) link is considered to support vehicular safety applications. Messages which are exchanged through a satellite link can be delivered to the destination without relying on RSUs or a multi-hop V2V link. Although the QoS requirement can be satisfied, such a solution is too expensive and probably will be considered in the future.

In [3], the authors leverage the multi-hop V2V link to enable video streaming in a highway VANET scenario. The proposed relay scheme can extend the coverage of an RSU and achieve a higher data rate. Also a video rate adaptation strategy is developed to adapt the video coding rate according to the current network condition so as to ensure the smooth and high-quality playback. However, this adaptive video streaming scheme cannot guarantee satisfactory performance when the vehicle density is low. Meanwhile, this scheme only considers one target vehicle which is downloading video packets, while the other vehicles only act as relay nodes.

In [16], the performance of an IEEE 802.11-based V2I uplink is investigated. It shows that, when the vehicle density increases, the per-vehicle throughput decreases. However, the performance of both the downlink and uplink is important since bidirectional applications such as VoIP are becoming popular. It is known that the voice packet delay must be less than a threshold to achieve an appropriate QoS guarantee. Apparently, this existing scheme cannot satisfy the QoS requirement of voice services and the performance would be even worse especially in a low density scenario.

In [17], an opportunistic relay protocol with a distributed feature is proposed. In this distributed relay protocol, instead of selecting a relay candidate before transmission, the RSU first broadcasts the data frame, and the vehicles that successfully receive the frame become the relay candidates. Each candidate independently determines its contention window according to its expected throughput to the destination. The priority is given to the candidate that is closer to the destination. The broadcast data rate is chosen to achieve the highest throughput according to the analysis in [17]. However, the best data rate selection scheme is not able to work perfectly due to the contentions of relay candidates. A large number of relay candidates can cause collisions especially in a high density scenario.

In [18], a distributed enhancement algorithm (DEA) for adaptive contention window size is proposed. In order to increase the throughput, the contention window has to be adaptive to the channel condition to decrease the collisions. In DEA, each vehicle counts the portion of busy time during the observation interval. The contention window is increased if the portion of busy time becomes larger. This algorithm only works when the density of vehicles is dynamic, but not for a stable vehicular network where the density stays the same.

It can be seen that these existing schemes need to be improved to simultaneously satisfy the QoS requirements of multiple services in different scenarios.

Chapter 3

Opportunistic Vehicle Relay with Adaptive Modulation

In this chapter, we present an opportunistic vehicle relay protocol with adaptive modulation to address the relay selection problem of drive-thru Internet. An analytical approach is developed to evaluate the access performance of the proposed vehicle relay protocol.

3.1 Relay Selection Problem

Drive-thru Internet [4] is a promising technique that exploits inter-connected RSUs to enable Internet access for vehicular users on the move. Different from the cellular networks that have ubiquitous coverage, the RSUs usually only provide intermittent connectivity due to the high costs of deploying and maintaining a large number of RSUs. In the literature, there have been many studies on engaging vehicle-to-vehicle (V2V) relay to further complement the limited coverage of roadside RSUs. Relay selection becomes an essential problem when deploying an access protocol in the drive-thru Internet.

In general, a centralized relay selection solution aims to identify the best relay(s) by exploiting a global view of the network so as to maximize the transmission success probability and minimize the collision probability. However, because such protocols require additional time to exchange channel state information, the incurred overhead and delay are often large.

An opportunistic relay protocol with a distributed feature is proposed in [17] for the drive-thru Internet. In the opportunistic relay protocol, the RSU first broadcasts the data and all vehicles that successfully receive the data contend to relay it to the destination. Each relay vehicle sets its contention window according to its distance to the destination. A priority (smaller contention window) is given to the vehicle with a higher expected data rate, i.e., generally closer to the destination. The study in [17] considers the tradeoff between the broadcast data rate and the achievable throughput. A lower broadcast rate with a large transmission range increases the number of relay candidates and the chance of having good relays. Nonetheless, the priority scheme is assumed to work perfectly. Actually, more candidates also lead to more intense contention in the forwarding. Hence, the analysis in [17] may not be able to determine the best broadcast rate, especially for a scenario of a high vehicle density.

In this thesis, we propose a new opportunistic V2V relay protocol. Due to the distributed contention nature, there is a probability that two or more relays time out within the collision interval. Hence, the proposed relay protocol needs to properly address the collisions that occur among the relay vehicles. Moreover, adaptive modulation at the RSU and the relay vehicles are taken into account to address the trade-off between involving a sufficient number of relay candidates and mitigating contention among them.

3.2 System Model

In this chapter, we consider the drive-thru Internet access system illustrated in Fig. 3.1, where vehicular users can access the Internet via the RSUs. In particular, we focus on one direction of a highway segment and the downlink communications from the RSU to a tagged vehicle D. According to the real vehicular traffic trace in [19], the inter-vehicle distance closely follows the exponential distribution. Hence, we assume that the vehicles are spatially distributed along the highway segment as a one-dimensional Poisson point process (PPP) with an intensity function λ (vehicles/m).

To characterize the wireless fading channel in the vehicular environment, we assume that the data transmission between a transmitter located at x and a receiver located at y is subject to Rayleigh fading. That is, the signal-to-noise ratio (SNR) of the received signal can be written as

$$\gamma_{xy} = \frac{P_t}{N_t} h_{xy} g_{xy} \tag{3.1}$$

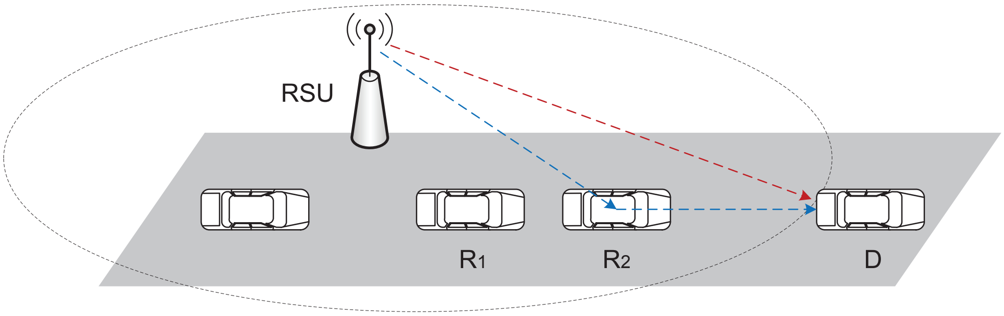


Figure 3.1: System model of drive-thru Internet access with V2V relay.

where P_t is the transmit power, N_t is the power of additive white Gaussian noise (AWGN), and h_{xy} denotes the small-scale channel fading which is exponentially distributed with unit mean. The path-loss effect is captured by $g_{xy} = \|x - y\|^{-\alpha}$, where $\|x - y\|$ is the Euclidean distance, and α is the path-loss exponent.

Assume that the RSU and vehicles adaptively select their modulation modes among binary phase-shift keying (BPSK) and square M-ary quadrature amplitude modulation (M-QAM). The bit error rates (BER) of BPSK and M-QAM are, respectively, given by

$$P_{BPSK} = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{3.2}$$

$$P_{QAM} = \frac{4}{k}\left(1 - \frac{1}{\sqrt{M}}\right)\text{Q}\left(\sqrt{\frac{3k}{M-1}\frac{E_b}{N_0}}\right) \tag{3.3}$$

where M is the constellation size, $k = \log_2 M$, and E_b/N_0 is the ratio of bit energy to noise power intensity. Here, $E_b/N_0 = \gamma_{xy} \cdot B_w/R_t$, where B_w is the channel bandwidth (Hz) and R_t is the transmission rate (bps) of the corresponding modulation mode. To successfully decode the received signal, we assume that the BER needs to satisfy a certain requirement. Accordingly, the received SNR should be no less than a threshold β [20]. Hence, the probability of correctly decoding a packet is given by

$$P_{xy} = \Pr\left[\gamma_{xy} \geq \beta\right] = \exp\left(\frac{-\beta}{P_t/N_t}\|x-y\|^{\alpha}\right). \tag{3.4}$$

We assume that each vehicle knows its own location, which can be obtained from its GPS receiver. Further, the location of the tagged vehicle D can also be piggybacked in the transmitted packet. It should be noted that the RSU is unnecessary to know the locations of the surrounding vehicles, and each relay vehicle does not have the location information of others either. As such, each relay vehicle R can estimate its transmission success probability P_{RD} to the destination D according to its location information and (3.4) and choose its backoff time as

$$W = (1 - P_{RD}) \cdot F \tag{3.5}$$

where the transmission time of a packet at the highest modulation rate is taken to be one time unit and the maximum backoff time is F time units. It is expected that a good relay vehicle ends up with a short backoff time while there is a small probability that two or more relays time out within an indistinguishable interval c when a collision occurs [21].

Let M_s and M_v denote the constellation sizes of the modulations of the source RSU and a relay vehicle, respectively. In the next section, we will present our analytical approach to determine the modulation modes.

3.3 Analysis of Proposed Scheme

Consider K modulation modes for the RSU and relay vehicles. Let β_i denote the decoding SNR threshold of the modulation mode i, $i = 1, \ldots, K$. Given that a modulation mode s is adopted by the RSU to broadcast a packet to the destination vehicle D, the success probability of the direct transmission is given by

$$P_{SD} = \exp\left(\frac{-\beta_s}{P_t/N_t} L^{\alpha}\right) \tag{3.6}$$

where P_t/N_t is the transmit SNR at the RSU and L is the distance between the RSU and D. Similarly, a neighbor vehicle of a distance r to the RSU can correctly overhear the packet with a probability

$$P_{SR}(r) = \exp\left(\frac{-\beta_s}{P_t/N_t} r^{\alpha}\right). \tag{3.7}$$

These vehicles that correctly overhear the packet are referred to as *potential relays*. Thus, the spatial distribution of the potential relays can be viewed as the result of a $p(x)$-thinning process [22], where the $p(x)$-thinning is a generalized operation that defines a retention probability $p(x)$ for each point of a PPP and yields a thinned point process by deleting the point with a probability $1 - p(x)$. According to Prekopa's Theorem [22], the resulting point process of these potential relays is also a PPP. The intensity measure is given by

$$\Lambda = \int_0^L \lambda P_{SR}(r)\,\mathrm{d}r. \tag{3.8}$$

When $\alpha = 2$, we obtain the closed-form expression of Λ as

$$\Lambda = \frac{\lambda}{2}\sqrt{\frac{\pi}{K_s}}\mathrm{erf}\left(\sqrt{K_s L}\right) \tag{3.9}$$

where $K_s = \frac{\beta_s}{P_t/N_t}$. Thus, the probability of having l potential relays is given by

$$\Pr\big[N_r = l\big] = \frac{\Lambda^l}{l!}e^{-\Lambda}, \qquad l = 0, 1, 2, \ldots \tag{3.10}$$

3.3.1 Statistics of Potential Relay Vehicles

Due to the probabilistic nature of the opportunistic V2V relay protocol, we first analyze the statistics of the potential relay vehicles in terms of their channel conditions, including the average received SNR from a potential relay to the destination D (denoted by $\overline{\gamma}_{RD}$) and the corresponding transmission success probability (denoted by P_{RD}).

According to the channel model in (3.1), we can write the cumulative distribution function (CDF) of $\overline{\gamma}_{RD}$ as

$$\begin{aligned} F_\gamma(x) = \Pr\left[\overline{\gamma}_{RD} \le x\right] &= \Pr\left[\frac{P_t}{N_t}\|R - D\|^{-\alpha} \le x\right] \\ &= \Pr\left[\|R - D\|^{\alpha} \ge \frac{P_t/N_t}{x}\right]. \end{aligned} \tag{3.11}$$

The CDF in (3.11) depends on the spatial distribution of the potential relay vehicles and it can be further expressed as

$$F_\gamma(x) = \frac{1}{\Lambda}\int_0^L \lambda P_{SR}(r)\cdot \mathbf{1}\left((L-r)^\alpha \geq \frac{P_t/N_t}{x}\right)\,\mathrm{d}r \tag{3.12}$$

where $\mathbf{1}(\cdot)$ is the indicator function, given by

$$\mathbf{1}(y) = \begin{cases} 1, & \text{if } y > 0 \\ 0, & \text{if } y \leq 0. \end{cases}$$

The ratio in (3.12) defines the fraction of the potential relays that satisfy the condition $\|R-D\|^\alpha \geq \frac{P_t/N_t}{x}$, for a given average received SNR x. When $\alpha = 2$, a closed-form expression is obtained as

$$F_\gamma(x) = \frac{\lambda}{2\Lambda}\sqrt{\frac{\pi}{K_s}}\operatorname{erf}\left(L\sqrt{K_s} - \sqrt{\frac{K_s P_t/N_t}{x}}\right). \tag{3.13}$$

Let $G_P(y)$ denote the CDF of the transmission success probabilities of the potential relay vehicles to the destination D. According to (3.4), we have

$$G_P(y) = \Pr\left[P_{RD} \leq y\right] = \Pr\left[\exp\left(\frac{-\beta_v}{P_t/N_t}\|R-D\|^\alpha\right) \leq y\right] \tag{3.14}$$

where β_v is the decoding SNR threshold if the relay vehicle forwards the overheard packet to D using a modulation mode v. Here, $G_P(y)$ in (3.14) is related to $F_\gamma(x)$ in (3.11) as follows:

$$\begin{aligned} G_P(y) &= \Pr\left[\frac{P_t}{N_t}\|R-D\|^{-\alpha} \leq \frac{-\beta_v}{\ln(y)}\right] \\ &= \Pr\left[\overline{\gamma}_{RD} \leq \frac{-\beta_v}{\ln(y)}\right] = F_\gamma\left(\frac{-\beta_v}{\ln(y)}\right). \end{aligned} \tag{3.15}$$

Based on the estimated transmission success probability, each relay vehicle can determine its backoff time individually according to (3.5). Then, we can write the CDF of the backoff time of the potential relay vehicles as

$$\begin{aligned} H_W(t) &= \Pr\big[(1-P_{RD})\cdot F \leq t\big] = \Pr\left[P_{RD} \geq 1-\frac{t}{F}\right] \\ &= 1-G_P\left(1-\frac{t}{F}\right). \end{aligned} \tag{3.16}$$

3.3.2 Packet Delay and Success Probability

Based on the analysis in the statistics of potential relay vehicles, we can further evaluate the average packet delay, denoted by $\overline{T}$, and the overall transmission success probability with the opportunistic V2V relay protocol, denoted by P_{suc}.

Since we use the time of transmitting a packet at the highest modulation rate as one time unit, the delay of the direct transmission from the RSU to D is then K/s time units if the RSU adopts a modulation mode s, where $s = 1, \ldots, K$. Similarly, the transmission time of a relay vehicle to D is K/v time units if the relay applies a modulation mode v, where $v = 1, \ldots, K$. In addition, the relay waits for a random backoff time according to its estimated transmission success probability to D. According to (3.16), we obtain the mean backoff time as

$$\overline{W} = \int_0^F \left[1 - H_W(t)\right] \mathrm{d}t. \tag{3.17}$$

The total average packet delay is then

$$\begin{aligned}\overline{T} &= P_{SD}\frac{K}{s} + (1 - P_{SD})\left(\frac{K}{s} + \overline{W} + \frac{K}{v}\right) \\ &= \frac{K}{s} + (1 - P_{SD})\left(\overline{W} + \frac{K}{v}\right).\end{aligned} \tag{3.18}$$

The overall transmission success probability depends on the direction transmission and the retransmission via the relay vehicles. Particularly, the retransmission is subject to both fading errors and collision loss. Hence, we have

$$P_{suc} = P_{SD} + (1 - P_{SD})\widetilde{P}_{RD} I_c \tag{3.19}$$

where I_c is the probability of no collision among the relay vehicles and $\widetilde{P}_{RD}$ is the average transmission success probability of the best relay that wins the contention.

Supposing that there are l vehicles ($l \geq 1$) that correctly overhear a packet from the RSU to D, we have $P_{RD,(1)} < P_{RD,(2)} < \ldots < P_{RD,(l)}$ denote the l order statistics of the transmission success probabilities of these potential relays. According to the opportunistic relay protocol, the best relay has the highest transmission success probability, $P_{RD,(l)}$, and the shortest backoff time. The CDF of $P_{RD,(l)}$ of the best relay among l candidates is given by $\big\{\Pr[P_{RD} \leq y]\big\}^{l}$. Hence, we can obtain the CDF of the highest transmission success probability among a random number of potential relays as

$$\widetilde{G}_P(y) = \sum_{l=1}^{\infty} \frac{\Lambda^l}{l!} e^{-\Lambda} \cdot \big[G_P(y)\big]^l. \tag{3.20}$$

Thus, the average transmission success probability is given by

$$\widetilde{P}_{RD} = \int_0^1 \big[1 - \widetilde{G}_P(y)\big] \, \mathrm{d}y. \tag{3.21}$$

Because the priority scheme that determines a random contention window does not work perfectly, we need to balance the trade-off of engaging more high-quality relays and mitigating their collisions. Given l potential relays that correctly overhear the packet, we denote the l order statistics of their backoff time by $W_{(1)} < W_{(2)} < \ldots < W_{(l)}$. In [21], the authors derive the joint probability density function (PDF) of the minimum and second minimum of l order statistics as well as the probability that the difference of the minimum and second minimum is greater than a constant. Based on their conclusion, if the difference of the minimum and second minimum backoff time is greater than a constant c, the probability of no collision is given by

$$\begin{aligned} I_c | l &= \Pr\big[W_{(2)} \geq W_{(1)} + c\big] \qquad (3.22) \\ &= l(l-1) \int_c^F h_W(t) \big[1 - H_W(t)\big]^{l-2} H_W(t-c) \, \mathrm{d}t \end{aligned}$$

where $h_W(t)$ is the PDF corresponding to the CDF in (3.16). Considering a random number of potential relays, we can obtain the overall probability of no collision as

$$I_c = \sum_{l=1}^{\infty} \frac{\Lambda^l}{l!} e^{-\Lambda} \cdot I_c|l. \tag{3.23}$$

Then, (3.21) to (3.23) can be applied to (3.19) to evaluate the overall success probability.

As seen from the above analysis, the access performance ($\overline{T}$ and P_{suc}) depends on the modulation mode of the RSU for the direct transmission and that of the relay vehicles for retransmission. The performance is also related to the environment such as the vehicle density. The proposed analysis well characterizes the impact of various aspects of the drive-thru Internet system and can be used to appropriately determine the modulation modes.

3.4 Discussion

In the analysis of proposed scheme, the communication type is restricted to the downlink from the RSU to a tagged vehicle D. Because the RSU and the vehicle node are treated fairly during the communication, the analysis results will be the same if we assume that the scenario is the uplink communication from the vehicle D to the RSU. The proposed scheme applies to both the downlink and uplink communications.

In the above analysis, the best modulation modes are selected given that the distance between RSU and the tagged vehicle D is fixed. As the tagged vehicle moves, which means that the distance between the transmitter and receiver changes dynamically, the best modulation modes need to be selected adaptively according to our analytical approach.

Although the proposed opportunistic relay scheme can enhance connectivity by taking advantage of vehicle relay and adaptive modulation, it may not be sufficient to support multiple services and guarantee their QoS requirements simultaneously. In the next chapter, another complementary solution will be presented to focus on the QoS guarantee for multiple services.

Chapter 4

Adaptive Collision Avoidance with Service Differentiation

In this chapter, we focus on the improvement of access performance and the support of multiple services in the vehicular network. Firstly, we propose a new algorithm which is able to change MAC layer parameters adaptively to improve the overall network performance according to the current vehicular environment. Then, a multi-service differentiation scheme is presented, which assigns an appropriate priority level for each specific packet and schedules the transmission order of the packets buffered in the RSU.

4.1 MAC Layer Enhancement

4.1.1 Adaptive MAC Layer Parameters

In observing the channel activities, the time interval between two successful transmissions is defined as a *Virtual Transmission Time* (VT) [23]. The VT consists of the idle time, collision time and successful transmission time. The idle time is the time when no node is transmitting. The collision time means the duration that more than two stations are transmitting at the same time. During the successful transmission time, the packet is delivered to the destination successfully. It is noted that the idle time and collision time need to be minimized to achieve a high throughput, which also means that the collisions among the stations should be reduced.

In wireless MAC protocols such as CSMA/CA, a contention window (CW) based backoff mechanism is often deployed to decrease the collisions that occur when more than two nodes start to transmit during the collision interval. At the beginning of the transmission, a node that is ready to transmit will sense the channel. If the channel is idle during an arbitration inter-frame space (AIFS), the node will send the frame immediately; otherwise it will choose a backoff time uniformly within the interval $[0, CW - 1]$, where the initial CW size equals $CW_{min} + 1$. If the subsequent transmission fails, the interval size will be doubled until the CW size reaches the value of CW_{max}. In a general MAC protocol, the parameters such as CW_{min} and CW_{max} are usually fixed. This often leads to undesired access performance in the vehicular environment, where these parameters should be adaptive to the dynamic environment. For example, if the density of the vehicles is sparse, the throughput of the drive-through Internet can increase by choosing a smaller backoff window size. The waiting time (idle time) is thus reduced and more packets can be sent during the same interval. When the number of concurrent transmitting vehicles is large, fixed CW parameters can lead to aggressive transmissions of the vehicles, so that the throughput becomes low due to the high probability of collision.

A DEA algorithm is proposed in [18] to adjust the contention window size of each vehicle in order to be adaptive to dynamic changes of the vehicular environment and achieve a high throughput. In the DEA algorithm, the proportion of the busy time over a VT is recorded during each observation interval (OI). Assume that each vehicle generates the packets at a constant bit rate. The increase of the proportion of the busy time implies that more vehicles come to contend for transmitting. Hence, each vehicle enlarges its own contention window to reduce the probability of collision. However, it is challenging to select the contention window size appropriately. If the vehicular environment is stable, which means that the density of vehicles stay similar, the DEA algorithm does not work because the proportion of the busy time remains at the same level. The OI defined in this algorithm also takes a large value, which means that this algorithm updates the contention window infrequently. Therefore, this algorithm is not able to capture the fast topology changes of the vehicular network.

4.1.2 Adaptive Contention Window Algorithm

In our study, instead of observing the ratio of channel busy time, we design another metric that captures the dynamics of arriving packets, so that each vehicle enlarges its contention window size when the number of arriving packets is considered increasing.

The proposed adaptive contention window (ACW) algorithm is based on the observation that when more packets are arriving into the drive-through Internet, the CW size needs to increase to reduce the number of collisions. We define a monitor interval (MI) which is much shorter than an OI defined in the DEA algorithm, so that our algorithm is able to follow the dynamic changes of the vehicular topology. At the MI i, the overall ratio of successful packet transmissions S_p^i is defined as

$$S_p^i = \frac{N_{ack}^i}{N_{pkt}^i} \tag{4.1}$$

where N_{ack}^i is the number of ACK received by all the vehicles and the RSU during the duration MI i, N_{pkt}^i is the number of packets sent by all the vehicles and the RSU in the MI i. The RSU participates in every transmission as the transmitter or receiver. At the end of each MI, the RSU is responsible for collecting the statistics of transmitted packets and ACK. The RSU compares the current S_p^i with the average of the overall packet transmission successful ratio S_p in the previous MIs and computes the difference α_i. If the value of α_i is positive, the RSU confirms that the previous CW adjustment action is correct and takes the same action in the current CW adjustment. On the other hand, if α_i is negative, the RSU will take the opposite action to change the CW size to the reasonable value.

Algorithm 1 shows the details of ACM. Here, among the actions of the CW adjustment, $CA^i = 1$ means that the CW size will be increased by CW_{init}; $CA^i = -1$ means that the CW size will be decreased by CW_{init}. In order to initiate the algorithm in the first MI, we tentatively set CA^1 to 1 to increase the CW size. At the end of each MI, the RSU calculates a new CW value according to the packet transmission successful ratio and broadcasts the new CW value in the update beacon packet to the vehicles in the coverage of the RSU.

4.2 Multi-service Differentiation

4.2.1 Priority Assignment

The Enhanced Distributed Channel Access (EDCA) mechanism proposed in IEEE 802.11e is designed for contention-based prioritized QoS support. There are four application categories (ACs) with different priorities: background traffic (BK), best effort traffic (BE), voice traffic (VO) and video traffic (VI). Each AC uses different AIFS and CW sizes to contend for the transmission opportunity. IEEE 802.11p for the vehicular network also adopts the EDCA mechanism. The detailed parameter settings in IEEE 802.11p are shown in Table 4.1.

Algorithm 1: ACW

```
$CW = CW_{init}$, $i = 1$
while $V_n > 0$ do //$V_n$ is the number of vehicles associating with RSU
    if end of $i^{th}$ MI then
        Calculate $S_p^i$
        $\alpha_i = S_p^i - S_p$ //Calculate difference from previous MI
        //Determine adjustment action $CA^i$
        if $i == 1$ then
            $CA^i = 1$
        else
            if $\alpha_i > 0$ then
                $CA^i = CA^{i-1}$
            else
                $CA^i = -CA^{i-1}$
            end if
        end if
        $CW = CW + CA^i \cdot CW_{init}$ //Update contention window
        $S_p = \frac{S_p \cdot (i-1) + S_p^i}{i}$ //Update packet transmission successful ratio
        $i = i + 1$
    else
        Use previous CW
        Update variables
    end if
end while
```

Table 4.1: Default parameters in IEEE 802.11p.

AC	$CW_{min}[AC]$	$CW_{MAX}[AC]$	**AIFSN[AC]**
BK	15	1023	9
BE	7	1023	6
VI	3	15	3
VO	3	7	2

Table 4.2: Modified parameters for this study.

AC	$CW_{min}[AC]$	$CW_{MAX}[AC]$	**AIFSN[AC]**	**PW[AC]**
DA	15	1023	9	1
VI	7	64	6	2
VO	3	7	2	3

In this thesis, we also consider EDCA to support three different application categories: normal data traffic (DA), video traffic (VI) and voice traffic (VO). To achieve a better QoS performance, we extend the original parameter settings. The priority weight (PW) is introduced to differentiate the QoS of the different application traffic. The modified parameter settings are given in Table 4.2.

In the drive-through Internet, the DA traffic consists of the uplink packets sent by the vehicles. The users in the vehicles can also have video streaming traffic in the downlink from the RSU. The VO packets are transmitted in both directions between the RSU and the vehicles alternatively. If both the RSU and the vehicles are assigned with the same parameter settings in Table 4.2, the QoS requirement cannot be guaranteed as in the original EDCA mechanism. In most situations, the RSU has more packets to send compared with the vehicle nodes. As a result, the VO packets from the

RSU often experience the larger delay because the number of VO packets from the RSU is almost equal to the total amount of all the VO packets from the vehicles. The throughput of the VI traffic can be extremely low when a great number of neighbor vehicles are transmitting the DA traffic. Hence, the RSU which has more transmitting packets should be assigned with a higher priority. In our study, we assume that the setting of the RSU keep the same as shown in Table 4.2 but the initial CW sizes of the vehicles will change according to the distribution of the current ACs. Certainly, the modified CW sizes of the vehicles are larger than the original sizes of the RSU. Therefore, the packets from the RSU will occupy more transmission opportunities compared with the packets sent by the vehicles.

There are several related factors that need to be considered in the initial CW size assignment of the vehicles. For the DA traffic with the lowest priority, it increases the CW size not only to reduce the collisions that happen between the same traffic packets but also to release transmission opportunities to other packets which have the higher priority. Hence, the initial CW size of the DA traffic is determined by the distribution of DA, VI, and VO vehicles. We observed in our experiments that the CW size of the DA traffic needs to increase sharply when there is a high vehicle density. This is to ensure that the high-priority traffic is not blocked, while the low-priority DA traffic also has a transmission opportunity. We tested different increasing scales for the CW size of the DA traffic and found that the power law could work effectively. The power exponent should be selected appropriately so that the DA traffic is not substantially deprived of transmission opportunities and the overall throughput can be maximized.

As a result, the initial CW size of the DA traffic for the vehicles is given by

$$\begin{aligned} CW_{min}^{init}[DA] = \Big(& CW_{min}[DA] \cdot N_{da} \cdot PW[DA] + CW_{min}[VI] \cdot N_{vi} \cdot PW[VI] \\ & + CW_{min}[VO] \cdot N_{vo} \cdot PW[VO] \Big) \cdot \left(\left(\frac{\lambda_c}{\lambda_{min}} \right)^3 + C_\lambda \right) \end{aligned} \tag{4.2}$$

where N_{da} is the number of DA vehicles, N_{vi} is the number of VI vehicles, N_{vo} is the number of VO vehicles, λ_c is the current density of the vehicles, $PW[DA]$, $PW[VI]$, $PW[VO]$ are the priority weights of DA, VI, VO traffic, respectively, and $CW_{min}[VI]$, $CW_{min}[VO]$ are the contention window size for video and voice traffic, respectively. Moreover, λ_{min} is the minimum value of the vehicle density defined in the simulation, and C_λ is a constant value. The last term in (4.2) captures the increase scale of the contention window of DA traffic according to a power function of the vehicle density.

Because all the VI packets are transmitted by the RSU, it is not necessary to assign a new CW size of the VI traffic for the vehicles, but keeps the same setting as in Table 4.2. For the VO traffic with the highest priority, the initial CW size needs to keep a small value to win the contention with other traffics and achieve a low delay. However, the initial CW size of the VO traffic has to increase to avoid the internal collisions caused by the VO vehicles. As the high priority traffic, the VO traffic does not need to consider the number of DA and VI vehicles. To guarantee an affordable delay and throughput for the VO traffic, we assume that the initial CW size of the VO traffic increases linearly with the number of VO vehicles. As a result, the initial CW size of the VO vehicles can be expressed as

$$CW_{min}^{init}[VO] = CW_{min}[VO] + C_{vo} \cdot N_{vo} \tag{4.3}$$

where C_{vo} is a constant value.

For the ACW algorithm, only the overall transmission successful ratio needs to be redefined to support multiple services. The average packet size of each traffic is introduced to indicate the different contributions of different services for the overall network throughput. The new overall transmission successful ratio can be expressed as

$$S_p^i = \frac{N_{ack}^i[DA] \cdot L_{da} + N_{ack}^i[VI] \cdot L_{vi} + N_{ack}^i[VO] \cdot L_{vo}}{N_{pkt}^i[DA] \cdot L_{da} + N_{pkt}^i[VI] \cdot L_{vi} + N_{pkt}^i[VO] \cdot L_{vo}} \tag{4.4}$$

where L_{da} is the average packet size of the DA traffic, L_{vi} is the average packet size of the VI traffic, and L_{vo} is the average packet size of the VO traffic. Besides, $N_{ack}^i[DA]$, $N_{ack}^i[VI]$, and $N_{ack}^i[VO]$ are the number of ACK packets for data, video, and voice, respectively. Similarly, $N_{pkt}^i[DA]$, $N_{pkt}^i[VI]$, and $N_{pkt}^i[VO]$ are the number of sent packets for data, video, and voice, respectively.

4.2.2 RSU Internal Buffer Scheduling

There are two types of packets in the buffer of the RSU: the VI packets and VO packets. The simplest scheduling mechanism is that these packets are sent in the order of the arriving time. In this manner, the VO packets of a higher urgency may wait for a quite long time to transmit. The average delay of the VO packets will be the same as or even longer than that of the VI packets. In our scheme, the number of the transmitted VI packets, $N_{rsu}[VI]$, and the number of the transmitted VO packets, $N_{rsu}[VO]$, are controlled by a scheduling algorithm for the next transmission packet, so that

$$\frac{N_{rsu}[VI]}{N_{rsu}[VO]} = \frac{\frac{N_{vi} \cdot PW[VI]}{L_{vi}}}{\frac{N_{vo} \cdot PW[VO]}{L_{vo}}} . \tag{4.5}$$

With the RSU internal buffer scheduling, the packets with a high priority will not be blocked by the packets with a low priority and have prioritized transmission opportunities even when they arrive later than the low-priority packets. At the same time, the packets with a low priority can be sent if they get the transmission turns or there are no higher priority packets in the buffer.

4.3 Summary

It is worth noting that the QoS enhancement solution proposed in this chapter particularly focuses on multi-service support in drive-thru Internet. First, the ACW algorithm can adjust the CW size adaptively to decrease the collisions due to the inappropriate MAC layer parameters setting. Then, different priority weights are assigned to different services to distinguish their priorities in QoS assurance. The RSU buffer scheduling further complements the above components by properly arranging the transmission order of different buffered packets. When all components work together, we expect that the QoS requirements of multiple services can be satisfied in a more effective manner.

Chapter 5

Simulator Design and Implementation

In Chapter 3 and Chapter 4, we presented the QoS enhancement solutions for drive-thru Internet. To evaluate the performance of the proposed solutions, we also designed and implemented a vehicular network simulator. In this chapter, we describe the simulated scenario, including the road topology, the wireless communications technique (IEEE 802.11p), multiple services, and different vehicular traffic models. Then we present the overall simulation framework consisting of several modules and further explain the implementation of each module to provide a thorough understanding of the simulator.

5.1 Simulation Scenario

In this thesis, we consider a highway scenario shown in Fig. 5.1 as the default setting. The RSUs are uniformly placed along the road with an equal space. All RSUs are connected to the Internet backbone via high-speed wired links and an RSU can directly communicate with vehicles which are within its coverage. All vehicles are equipped with GPS devices to locate their positions and DSRC radios to communicate with other vehicles and RSUs. The channel conditions (fading, error rate, etc.) are also considered. For example, the bit error rate and transmission rate vary with the channel fading.

5.1.1 Network Topology

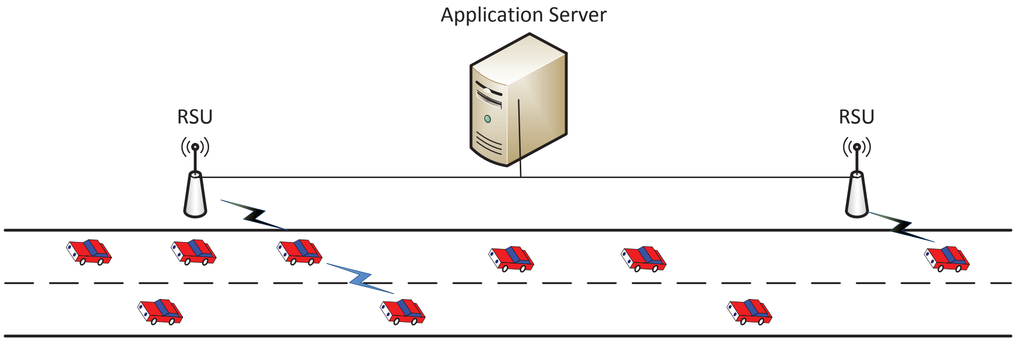


Figure 5.1: Highway VANET topology (adapted from [3]).

On the segment of the highway under study, the vehicle traffic is assumed unidirectional. The inter-arrival time of vehicles follows an exponential distribution. The vehicle behavior is specified by a trace file that is generated according to certain traffic model. The trace file of vehicles is produced after warming-up running for a sufficient period of time.

5.1.2 IEEE 802.11p

Compared with other standards, IEEE 802.11p is more suitable to provide an efficient communication method in the vehicular environment. FCC has allocated 75 MHz of licensed spectrum in the 5.9 GHz band for IEEE 802.11p, and the communication from other busy band (e.g, 2.4 GHz) cannot interfere the communication of IEEE 802.11p. At the MAC layer, the basic channel access is based on CSMA/CA. Also, IEEE 802.11p adopts OCB communications that do not need extra steps before transmission so as to adapt to the dynamic topology changes of vehicular networks.

5.1.3 Multiple Services

This research assumes that 3 types of different services should be supported simultaneously, which is a close assumption for the real environment. It is assumed that the data service is uni-directional for the uplink. The video service focuses on downlink streaming from an RSU to the specified vehicle. The voice service combines uplink and downlink communications together. Each vehicle can be assigned with one service type according to the simulation scenario.

5.1.4 Vehicular Traffic Models

Each vehicular traffic model describes some specified features that capture the essentials of the real traffic behaviors in building the model. Note that this traffic model is for the vehicles travelling on the specific highway segment. It is different from the data traffic models for multiple services. As the simplest traffic model, CSM does not consider surroundings to determine the behaviors of the vehicles. According to the CSM model, all vehicles determine their speeds randomly and keep the same all the time. In the FTM model, the speed of the vehicle changes with the dynamics of the average vehicle density. When the average vehicle density increases, which means the road becomes more crowded, the speed of the vehicles slows down. Compared with CSM and FTM models, IDM-LC is more realistic. The vehicle in the IDM-LC changes its speed dynamically according to the behavior of the front and the back vehicles. Also, a vehicle can change lane if the acceleration in the new lane is larger.

5.2 Simulator Framework

To examine the effects of different schemes and factors on the achieved throughput and delay, we build a computer simulation program with MATLAB 7.14.0 (R2012a) [24]. Fig. 5.2 depicts the simulation framework in

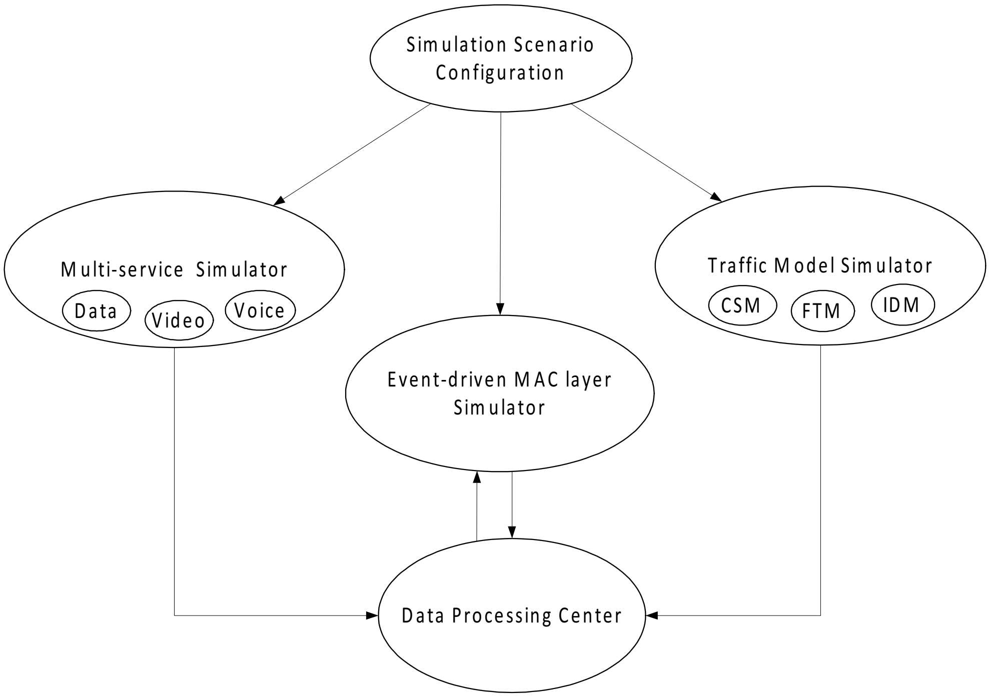


Figure 5.2: Simulator framework.

detail, including different modules of the simulator and their relationship to each other.

The simulator contains three major modules, i.e., traffic model simulator, multi-service simulator and event-driven MAC layer simulator. Due to the independence of the major modules, additional supplementary modules (simulation scenario configuration, data processing center) are necessary to connect the major modules together as a complete simulator.

Before we present further details of different modules, We first introduce the brief operation procedure of the whole simulator for a good understanding of the design of each separate module. At the very beginning, we need to choose a specific scenario to trigger the operations of the simulation. All parameters about the scenario can be defined in the module of simulation scenario configuration. Then according to the traffic model specified in the simulation scenario configuration, the traffic model simulator produces the trace file, which includes the moving information of the vehicles during the simulation time. At the same time, the service assignment of the scenario configuration is provided for the multi-service simulator to produce the packet information (service type, packet size, generating time). When the configuration information is ready, the data processing center combines the service and traffic data together to generate the packet arriving events. The event-driven MAC layer simulator implements the event processing rules according to the scheme that is to be tested and defined in the simulation scenario. The packet arriving events are delivered to the event-driven MAC layer simulation in the order of time. After the processing of the MAC layer simulator, the results of packet transmission are sent back to the data processing center. At last, the delay and throughput results can be plotted in the figures at the end of the simulation to present the effects of the tested scheme.

5.3 Traffic Model Simulator

The traffic model simulator is able to create three types of vehicular trace (CSM, FTM, and IDM). After the traffic module loads the traffic setting from the simulation scenario configuration file, the simulation of traffic trace can start. Based on the parameters for road topology and vehicle distribution, the road topology is created and each vehicle is placed on the road according to the defined location distribution. Then all vehicles begin to move following the indicated behavior rules of the chosen traffic model. The movement information of vehicle is recorded in the trace file after a sufficient period of warm-up running. At last, the trace file including the traffic records is stored in the data processing center.

5.4 Multi-service Simulator

For the multi-service simulator, it involves three different service models, which are data service, video service, and voice service. The data service contains only uplink packets that reside in the buffer of the vehicle. The downlink video packets, which are dispatched from the video server, are stored in the buffer of an RSU and be ready to be forwarded to the corresponding vehicle when the communication link is available. The voice service includes both the uplink and the downlink packets, which are transmitted alternately according to the feature of voice service. At first, the multi-service simulator loads the service assignment condition from the simulation scenario configuration file. Then the packet information (packet size, generating time, etc.) can be created during the operations of the service simulation. Finally, all the packet information is sent to the data processing center.

5.5 Event-driven MAC Layer Simulator

The MAC layer simulator is built according to basic model of the distributed coordination function (DCF) of IEEE 802.11. Each station needs to contend to access the channel with its specified priority. The simulator is designed as event-driven to improve the efficiency of the simulation. Different events represent different situations in the real transmission. When a new event occurs, this event is inserted in an event queue and waits to be handled. The popping events drive the simulation to move further until all these events are handled or the simulation time is up.

In the MAC-layer simulator, there are six events that represent different situations. The relationships of these events can be described clearly in

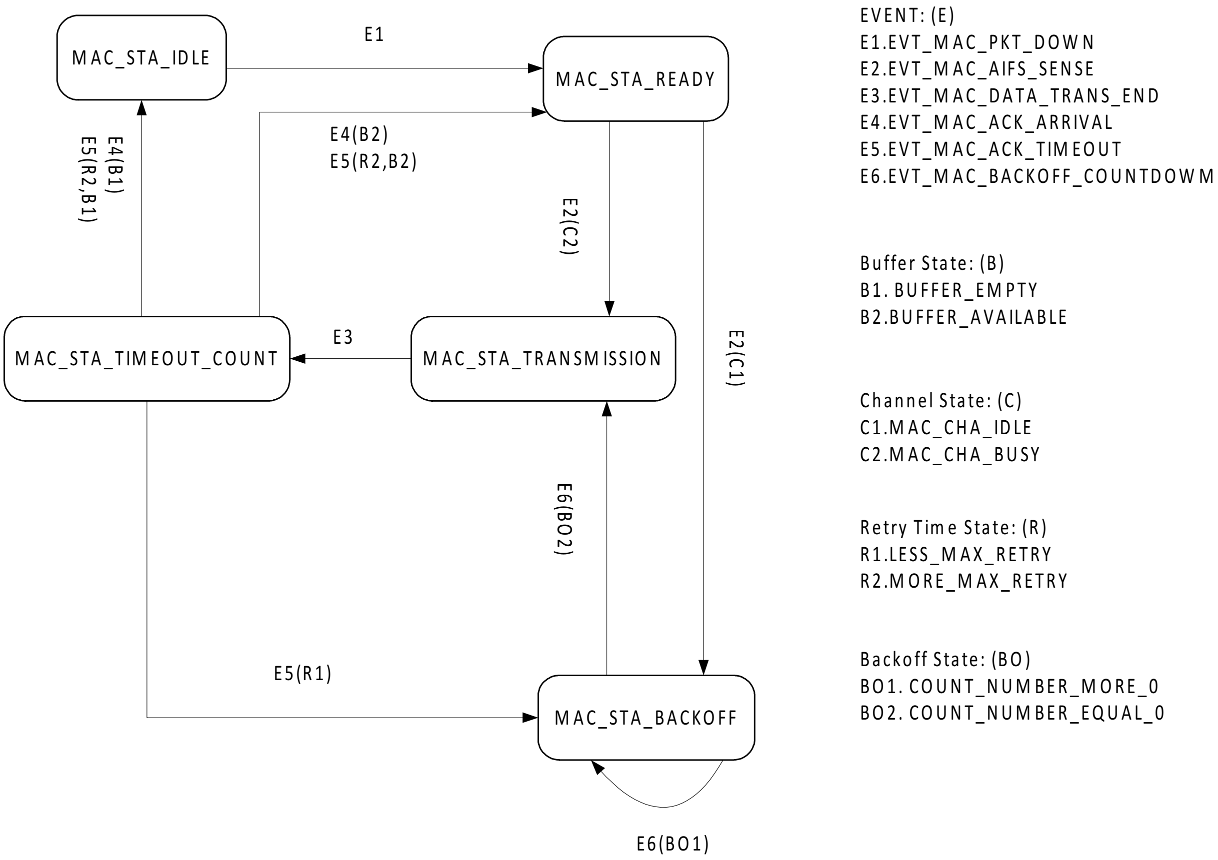


Figure 5.3: Event-driven state transition for MAC layer simulator.

Fig. 5.3. It shows that the status of the station is divided into five stages: idle, ready, backing off, transmitting, and timeout count. The six events drive the status of the station from one state to another. Following the generation of the subsequent events, the simulation is able to move forward.

1. **Station states**

   - `MAC_STA_IDLE`

     A station in the idle state, i.e., `MAC_STA_IDLE`, has no more packets to send at this moment. At the start of the simulation, the states of all stations are initialized to `MAC_STA_IDLE`.

   - `MAC_STA_READY`

     A station in the ready state, i.e., `MAC_STA_READY`, means that it is ready to start the transmission. However, before the station is able to transmit the packets, it needs to wait for an arbitration inter-frame space (AIFS) period in which the channel status is idle.

   - `MAC_STA_TRANSMISSION`

     The state of transmitting, i.e., `MAC_STA_TRANSMISSION`, is simple. It indicates that the station is transmitting a packet.

   - `MAC_STA_BACKOFF`

     If the channel is busy when a station in the state `MAC_STA_READY` attempts to transmit a packet, it has to shift into `MAC_STA_BACKOFF` and start the backoff procedure. Meanwhile, if the sender cannot wait for the arriving of the ACK at the end of timeout period and the retry time does not reach the maximum number, the station also transits to the state of `MAC_STA_BACKOFF`. The backoff counter only counts down when the channel is idle; otherwise the counter is frozen.

- `MAC_STA_TIMEOUT_COUNT`

  The state `MAC_STA_TIMEOUT_COUNT` means that the station is waiting for the ACK packet after transmitting a packet. No matter in which state the channel is, the timeout counter counts down unless it is interrupted by the arriving of the ACK packet or the timeout counter reaches 0.

2. **Events**

   - `EVT_MAC_PKT_DOWN`

     In our simulator, the event `EVT_MAC_PKT_DOWN` represents that a packet arrives at the MAC layer from the upper layer, or the ACK packet is returned due to the receiving a packet from other stations correctly. When this event happens, the station may act differently depending on the current station status. If the station is in the state of `MAC_STA_IDLE`, it will transit to the state of `MAC_STA_READY`. Meanwhile, the packet will be stored in the buffer of the station, and the buffer state will transit from the state of `BUFFER_EMPTY` to the state of `BUFFER_AVAILABLE`. However, if the packet arrives when the station is in other states, the station will keep the current state other than store the packet in the buffer of the station.

- `EVT_MAC_AIFS_SENSE`

  Before a station starts transmitting a new packet, it is required to wait for an AIFS so that the channel can be considered as available. During the event `EVT_MAC_AIFS_SENSE`, if the state of the channel becomes busy, the station will transit to the state of `MAC_STA_BACKOFF`. Conversely, if the channel is idle during the event of `EVT_MAC_AIFS_SENSE`, the state will shift to the state of `MAC_STA_TRANSMISSION` and the packet is transmitted immediately.

- `EVT_MAC_DATA_TRANS_END`

  This event `EVT_MAC_DATA_TRANS_END` is simple and easy to understand. It means that the station just finishes the transmission of the packet. No matter whether the collision occurs or not, the station will transit to the state of `MAC_STA_TIMEOUT_COUNT` to count down the timeout counter and wait for the packet of ACK.

- `EVT_MAC_ACK_ARRIVAL`

  The event `EVT_MAC_ACK_ARRIVAL` represents that the ACK has arrived at the sender. Because the ACK packet involves the arriving time of the service packet, the delay can be calculated at this moment. After the event `EVT_MAC_ACK_ARRIVAL`, the station state can change immediately according to the current state of the buffer in the station. The station will move to the state of `MAC_STA_IDLE` when the buffer is empty. If there are any packets in the buffer, the station will shift to the state of `MAC_STA_READY`.

- `EVT_MAC_ACK_TIMEOUT`

  In the simulation, a collision may happen when more than two stations are transmitting at the same period so that the packet cannot arrive at the receiver successfully. Besides, the channel fading will also lead to the failure of receiving the packet correctly. In the above two cases, the receiver is not able to generate the ACK and the sender will not get the ACK during the timeout period. Then the event `EVT_MAC_ACK_TIMEOUT` occurs. In this situation, three different state changes will occur due to the different situations. If the retry times is less than the maximum limit, the state will switch to the state of `MAC_STA_BACKOFF` and prepare for the next transmission. The packet will be dropped when the number of retries reaches the maximum limit. Meanwhile, the state will shift to the state of `MAC_STA_IDLE` when the station has no packet to transmit. Or, the station is going to send the next packet in the state of `MAC_STA_READY`.

- `EVT_MAC_BACKOFF_COUNTDOWN`

  Each station maintains a backoff counter and a contention window for the operation of random backoff process, which intends to decrease the collisions. The counter is assigned a random value within this contention window at the beginning of each backoff process. Because the backoff counter keeps frozen when the channel is busy, the event `EVT_MAC_BACKOFF_COUNTDOWN` only happens when the channel is idle. At the end of one time slot, if the channel is idle and the counter is greater than 0, the station will decrease the counter by one and still reside in the state of `MAC_STA_BACKOFF`. However, when the channel is idle and the counter is equal to 0, it means that the backoff process ends and the station will shift to the state of `MAC_STA_TRANSMISSION` to transmit the packet immediately.

Chapter 6

Experiment Results and Discussions

We proposed the opportunistic relay with adaptive modulation scheme in Chapter 3 and the adaptive collision avoidance with service differentiation scheme in Chapter 4. The design and implementation of the vehicular network simulator have been described in Chapter 5. In this chapter, we first validate the theoretical analysis for the opportunistic relay scheme proposed in Chapter 3. Then, we evaluate the two schemes proposed in Chapter 3 and Chapter 4 in the specified simulation scenarios. The performance of the two schemes combined together is also investigated with our simulator.

Table 6.1: System parameters.

Definition	**Symbol**	**Value**
Distance between RSU and D	L	1000 m
Channel bandwidth	B_w	22 MHz
Number of modulation modes	K	6
Minimum success probability	P_{suc}	0.8
Collision interval	c	0.01 time units
Maximum backoff time	F	5 time units
Transmit SNR	P_t/N_t	55 dB
Path loss exponent	α	2
Vehicle density	λ	0.05 $\sim$ 0.25 vehicles/m

6.1 Validation of Theoretical Analysis

In this section, we verify with simulations the theoretical analytical approach that we developed in Chapter 3 for the opportunistic relay with adaptive modulation scheme. The testing system parameters are given in Table 6.1.

6.1.1 Analysis Accuracy

Fig. 6.1 compares the analysis results with the proposed approach to the simulation results against the vehicle density λ. As seen, the analysis and simulation results match well for both the packet delay and success probability. The overall success probability meets the required minimum bound. However, there is a turning point of the average packet delay when the vehicle density is 0.19. As the vehicle density increases from zero, the delay

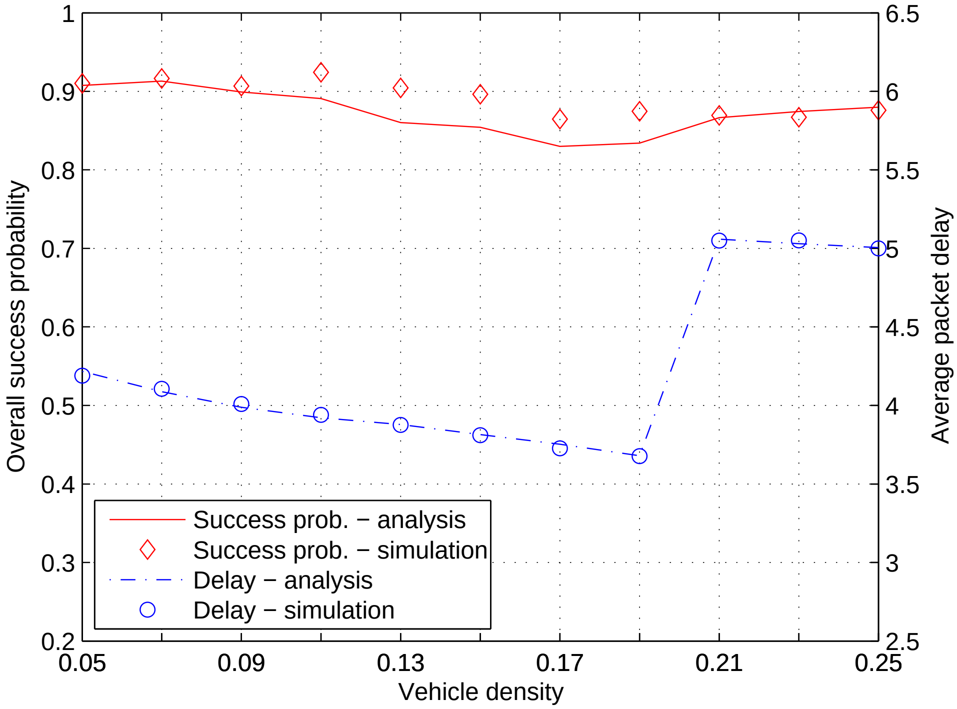
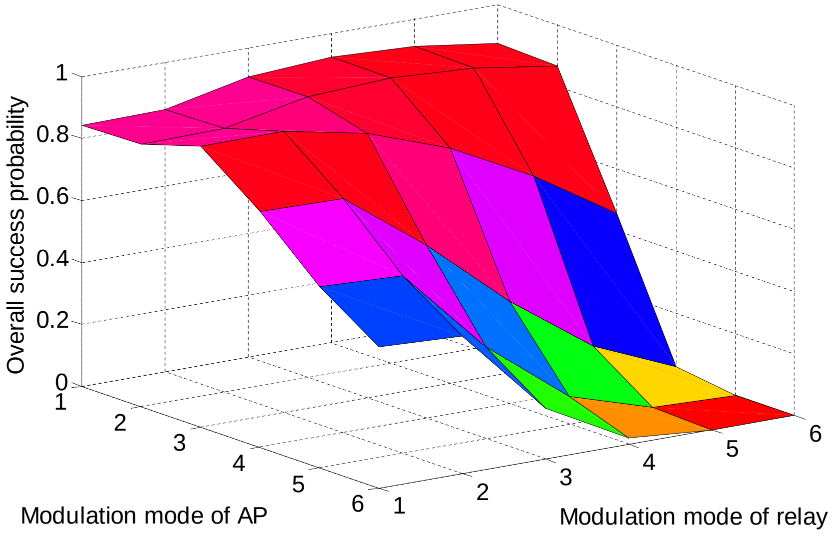


Figure 6.1: Analysis and simulation results of overall success probability and average packet delay.

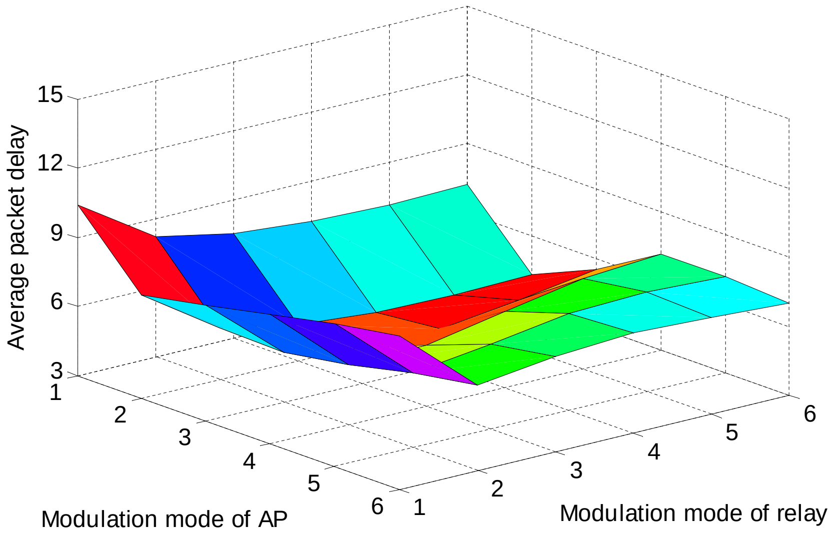
decreases because there are more vehicles on the road and the probability of finding a good relay is higher with more relays. Then the vehicle density reaches the turning point which has a high density. The collisions among relays increase significantly and lead to a longer delay.

6.1.2 Effectiveness

Fig. 6.2 demonstrates the variation of the access performance with the modulation modes of the AP and the relay vehicles. When a minimum trans-



(a) Overall success probability.



(b) Average packet delay.

Figure 6.2: Variation of overall success probability and average packet delay with modulation modes.

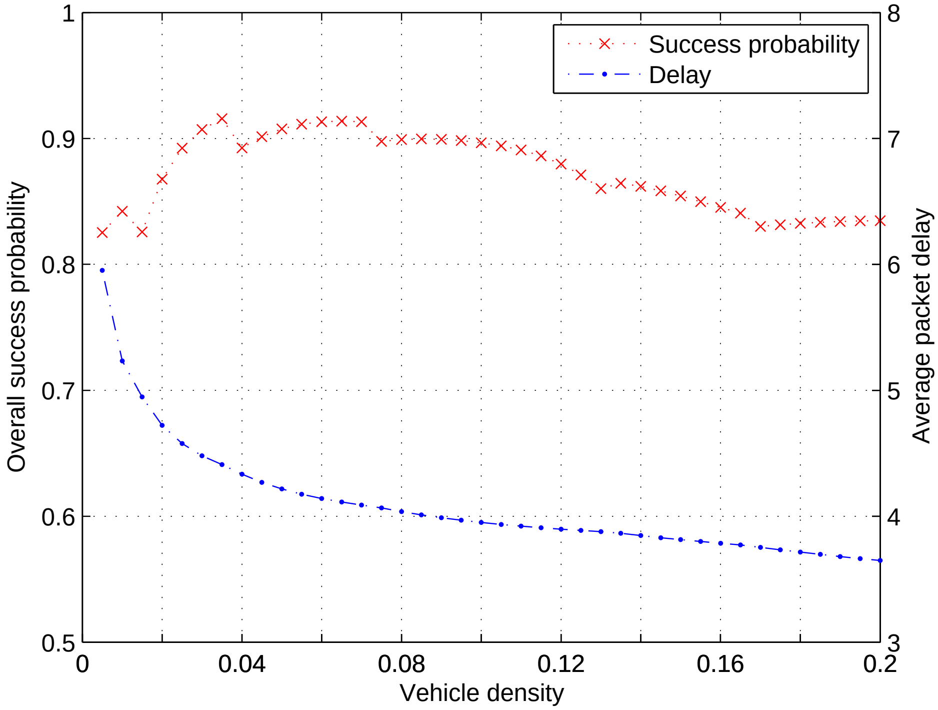


Figure 6.3: Overall success probability and average packet delay with modulations adapted with vehicle density.

mission success probability is set, the best modulation modes can be determined to guarantee the packet delay is minimized. Given a requirement that $P_{suc} \geq 0.8$, Fig. 6.3 shows the access performance with adaptive modulation modes selected by our analytical approach. Clearly, the overall success probability meets the required minimum bound. This is because the modulation modes can be effectively adapted with our analysis to balance the trade-off between engaging good relay candidates for a higher data rate and more intense collisions with more contending relays.

6.2 Simulation Settings

In the remaining of Chapter 6, we evaluate the performance of the proposed QoS enhancement solutions (including the opportunistic relay scheme and the adaptive collision scheme) in multi-service settings. The performance of the proposed solutions is also compared with representative existing solutions. In this section, we provide the general settings for the simulations. At the beginning of each simulation run, the scenario of the simulation needs to be specified in the configuration file and deployed into the simulator. Consider one example scenario where each vehicle on the highway is randomly assigned one type of applications (VO, VI, DA) for the passengers on the move. The packets are transmitted between the vehicle nodes and the RSU which is located in the middle of the highway segment. The RSU is connected through the edge router to the Internet. The detailed simulation

Table 6.2: The overall simulation parameters.

Definition	Symbol	Value
Length of highway segment	L_{hw}	2000 m
Time of simulation	T_s	10 s
Channel bandwidth	B_w	22 MHz
Number of modulation modes	K	6
Data rate of each modulation mode	R_k	2, 4, 8, 16, 32, 64 Mbps
Transmit SNR	P_t/N_t	55 dB
Path loss exponent	α	2

Table 6.3: FTM traffic model parameters.

Definition	Symbol	Value
Maximum speed of the fast vehicle	S_f	100 km/h
Time of warm-up	T_w	100 s
Vehicle density	λ	0.02 $\sim$ 0.18 vehicles/m
Vehicle density interval	$\Delta\lambda$	0.02 vehicles/m

parameter setting for the above scenario is described in Table 6.2.

We consider the FTM traffic model, which is the most widely used. In this case, we use the FTM vehicle mobility model to generate the trace file, following the parameters given in Table 6.3.

There are 3 types of ACs available in the simulation: high priority VO traffic flow, VI traffic flow with medium priority, and DA traffic with low priority. The different traffic flows are described in Table 6.4. Here, the percentages

Table 6.4: Description of traffic flows.

AC	Date rate	Packet size
DA	40 kbps	1000 bytes
VI	120 kbps	500 bytes
VO	16 kbps	100 bytes

of DA, VI, and VO application users are 40%, 10%, and 50%, respectively. The vehicles on the road are assigned with one type application randomly. This scenario is referred to as the multi-service scenario.

The parameters of the opportunistic relay scheme and the adaptive contention avoidance scheme can be found in the Chapter 4 and Chapter 5, respectively. The major parameters for the MAC layer setting are chosen based on the IEEE 802.11p [6].

6.3 Results of Opportunistic Relay with Adaptive Modulation

In this section, we firstly evaluate the performance of the opportunistic relay scheme in the uplink scenario. The uplink scenario includes only the DA traffic users, which is consistent with our analysis for the scheme of opportunistic relay with adaptive modulation in Chapter 4. Except the distribution of AC traffic, the parameter settings of the uplink scenario and multi-service scenario are the same.

For comparison purposes, we consider three different schemes. The `Standard` scheme only allows the vehicle to directly communicate with the RSU using the standard IEEE 802.11p protocol. The `Relay` scheme enables the vehicle to access the Internet via both V2I and V2V according to the relay scheme in [3]. In our proposed `ORAM` scheme, which is the opportunistic relay with adaptive modulation, we further introduce adaptive modulation in addition to opportunistic relay.

Fig. 6.4 shows the overall throughput in the vehicular network with the above three schemes. It can be seen that the throughput of the `ORAM` is significantly better than the other schemes. Counter-intuitively, the `Standard` scheme even outperforms the `Relay` scheme. This is because the `Relay` scheme simply considers the relay vehicle closest to the RSU as the best relay node, which cannot select the most appropriate relay vehicle.

It can be seen in Fig. 6.4 that there are two special points when the vehicle density is in the range of (0.1, 0.12). This observation can be interpreted as follows. First, when the vehicle density is low, `ORAM` can choose a low-rate modulation to engage more relay vehicles such that the overall throughput is increasing fast with the vehicle density. On the other hand, when the vehicle density continues to increase, the collisions among the vehicles increase sharply, which drops the throughput. With adaptive modulation, `ORAM` can choose a high-rate modulation to reduce the number of potential relay candidates and their collisions. Thus, the throughput degrades more slowly. Because there are a limited number of modulation modes, the transmission rates of these modulation modes are rather distinct instead of continuous. At these two special points with a vehicle density in the range of (0.1, 0.12), `ORAM` cannot find an appropriate modulation mode in the finite set, which can satisfy the transmission success probability requirement and maximize the throughput at the same time. As a result, there is small fluctuation at these two special points.

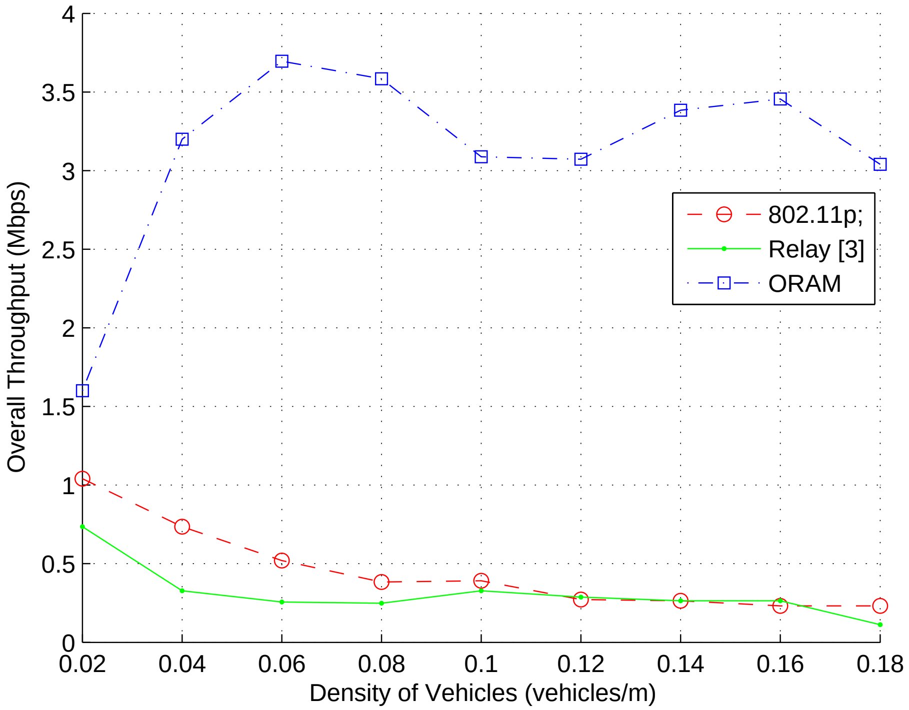


Figure 6.4: The overall throughput in the uplink scenario.

The average throughput per vehicle and the average delay of the three schemes are shown in Fig. 6.5 and Fig. 6.6, respectively. As observed, the performance of the `ORAM` scheme is much better than that of the other schemes, although the average delay and throughput become worse as the vehicle density increases. The results of the uplink scenario shows that the scheme `ORAM` is effective in the single DA traffic scenario.

Compared to the uplink scenario, the multi-service scenario is more realistic but more complex. Fig. 6.7 shows the overall throughput of all the nodes in the multi-service scenario. It is observed that the `ORAM` scheme is able to improve the overall network throughput in the multi-service scenario. Fig. 6.8 presents the average packet delay in the multi-service scenario. As seen, the delay of the `ORAM` scheme is lower than that of the other schemes only when the vehicle density is sparse. When the vehicle density is low, the high transmission success probability of the `ORAM` scheme guarantees a lower delay. As the vehicle density increases, the more intense contention also makes the delay larger.

For the performance of the `ORAM` scheme, the average throughput per vehicle and the average packet delay of different services are shown in Fig. 6.9 and Fig. 6.10, respectively. In Fig. 6.9, the average throughput per vehicle satisfies the requirements in Table 6.4 for all services when the vehicle density is low. As the density becomes high, the average throughput per vehicle of high priority services (VI, VO) becomes low. In contrast, the average throughput per vehicle of low priority traffic (DA) stays at a high level even

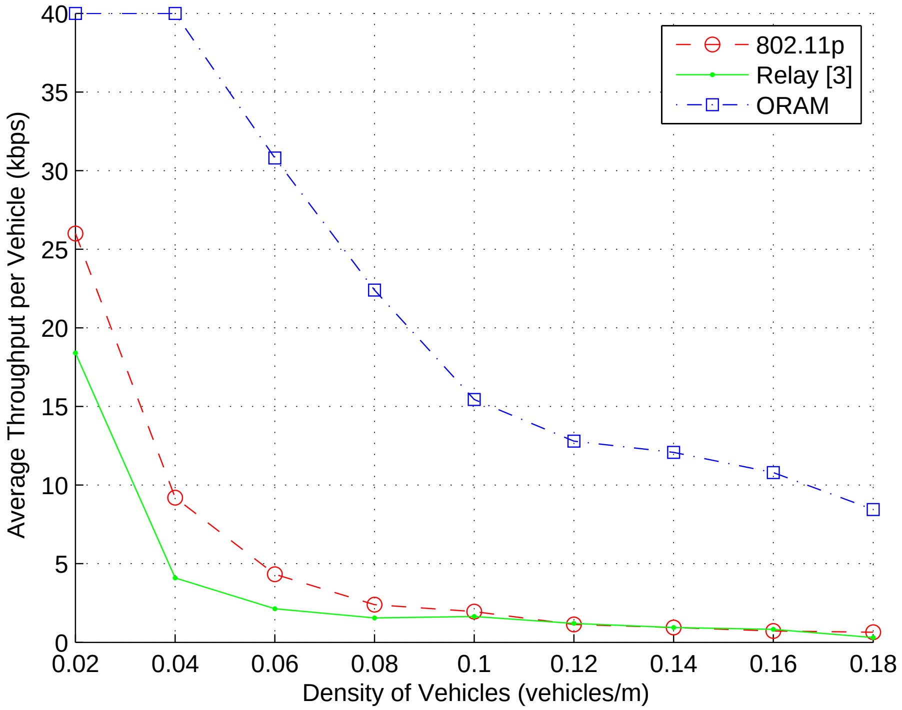


Figure 6.5: The average throughput per vehicle in the uplink scenario.

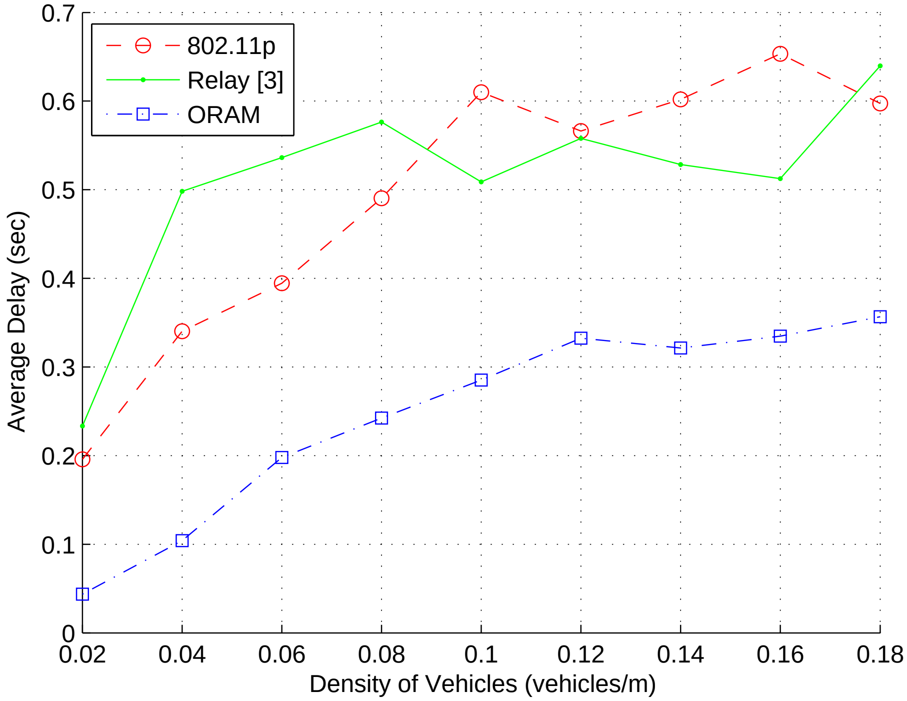


Figure 6.6: The average delay in the uplink scenario.

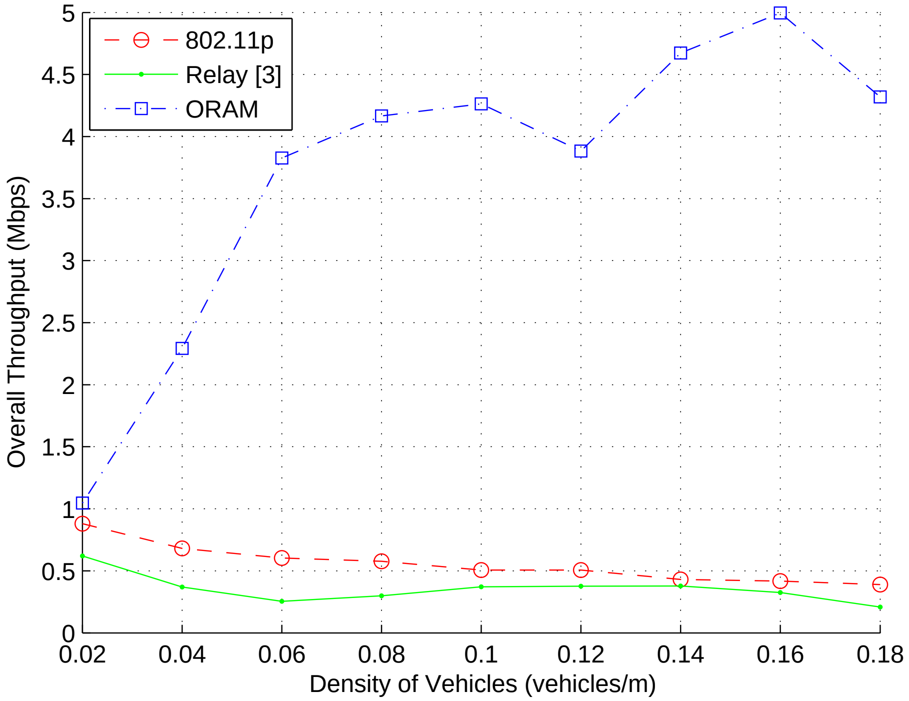


Figure 6.7: The overall throughput in the multi-service scenario.

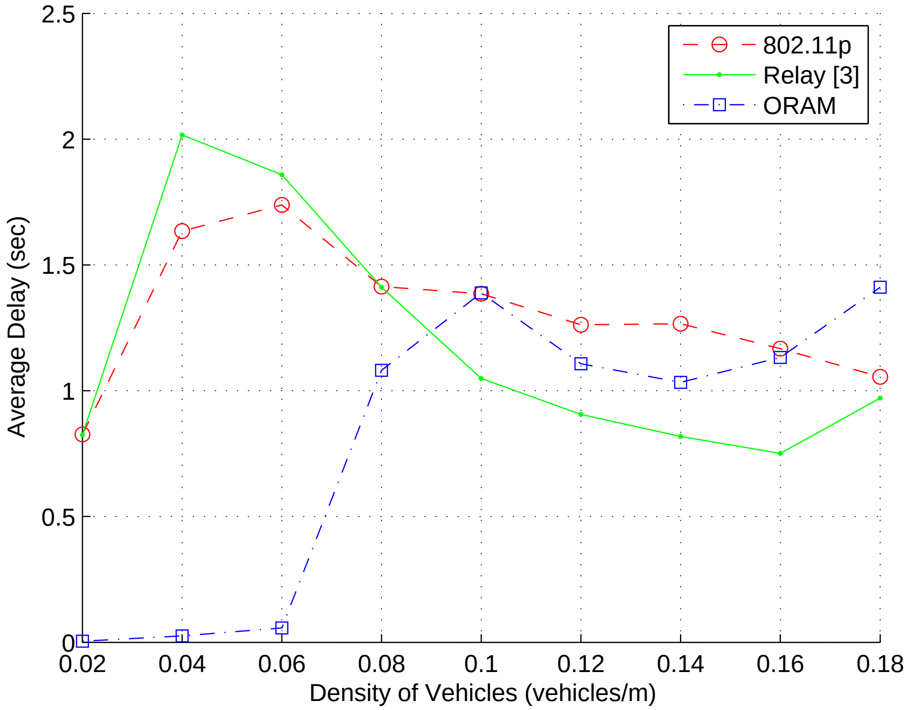


Figure 6.8: The average delay in the multi-service scenario.

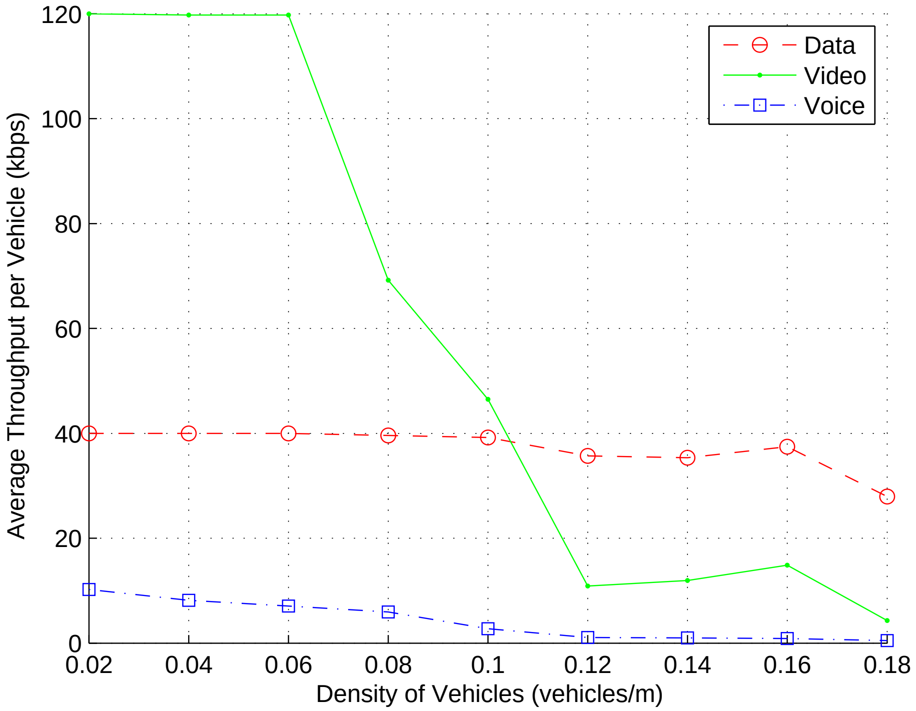


Figure 6.9: The average throughput per vehicle of different services in the multi-service scenario.

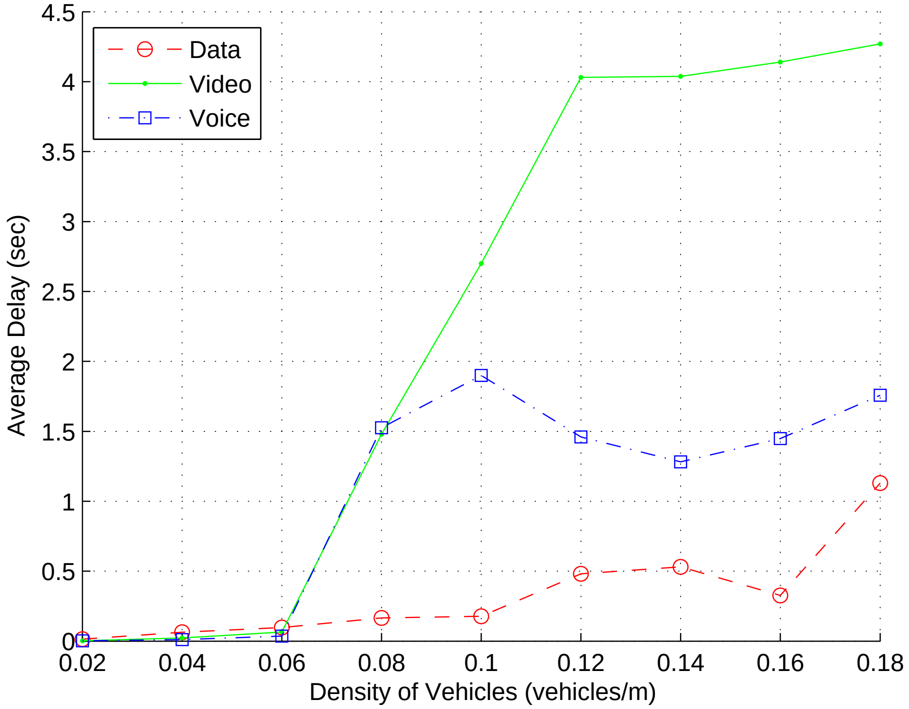


Figure 6.10: The average delay of different services in the multi-service scenario.

when the vehicle density is high. For the average packet delay of different services in Fig. 6.10, it can be seen that all services perform well in the low density situations. When the vehicle density becomes high, the average delay of the DA service still satisfies the delay requirement but the delay of other services (VI, VO) is larger than their requirements.

It is worth noting that the QoS of multiple services in the high vehicle density situations cannot be guaranteed by the `ORAM` scheme. As the `ORAM` scheme achieves a high transmission success probability, the packets can be delivered to the destination with a larger probability whenever the packets obtain access to the channel. Because the DA traffic has a packet size larger than those of the other types of traffic, the transmission of the DA traffic contributes more to the overall throughput. In the high vehicle density situations, because the network is congested, the DA traffic of a larger packet size may occupy the channel for a long duration so that the packets of the high-priority traffic experience a long waiting time to be transmitted. Till the end of the simulation, many high-priority packets may be still queued for transmission, while the DA packets have been delivered to the destination.

6.4 Results of Adaptive Collision Avoidance with Service Differentiation

In this section, we compare the performance of the proposed adaptive collision avoidance with service differentiation scheme (`ACASD`) with that of two other schemes. One is the `Standard` scheme following IEEE 802.11p. The other one is the `DEA` scheme proposed in [18] which monitors the portion of the busy time and changes the CW size to improve the access performance. The experiments are conducted in the multi-service scenario. The overall throughput and the overall average delay are shown in Fig. 6.11 and Fig. 6.12, respectively. It is clearly observed that the `ACASD` scheme performs better than the other two schemes in most situations, although the average delay is slightly higher in some extremely dense scenarios. This is reasonable since the size of CW increases with the growth of the vehicle density and a larger CW size will lead to a longer delay.

To demonstrate the performance of service differentiation with the `ACASD` scheme, Fig. 6.13 and Fig. 6.14 show the average throughput per vehicle and the average delay of different services, respectively. The results demonstrate that the VO traffic with a high priority achieves a better performance than the traffic with a low priority. However, the throughput of the VI traffic drops faster than that of the DA traffic. In this multi-service scenario, the network is always saturated. The channel resource is scarce and needs to be reserved for the high priority packets. The VI and VO packets are all transmitted through the RSU. The VI packets must contend with the VO packets in the internal of the RSU before accessing the channel. The opportunity of accessing the channel must be reserved for the VO traffic which has a highest priority. Thus, the chances for the VI traffic to access the channel become less.

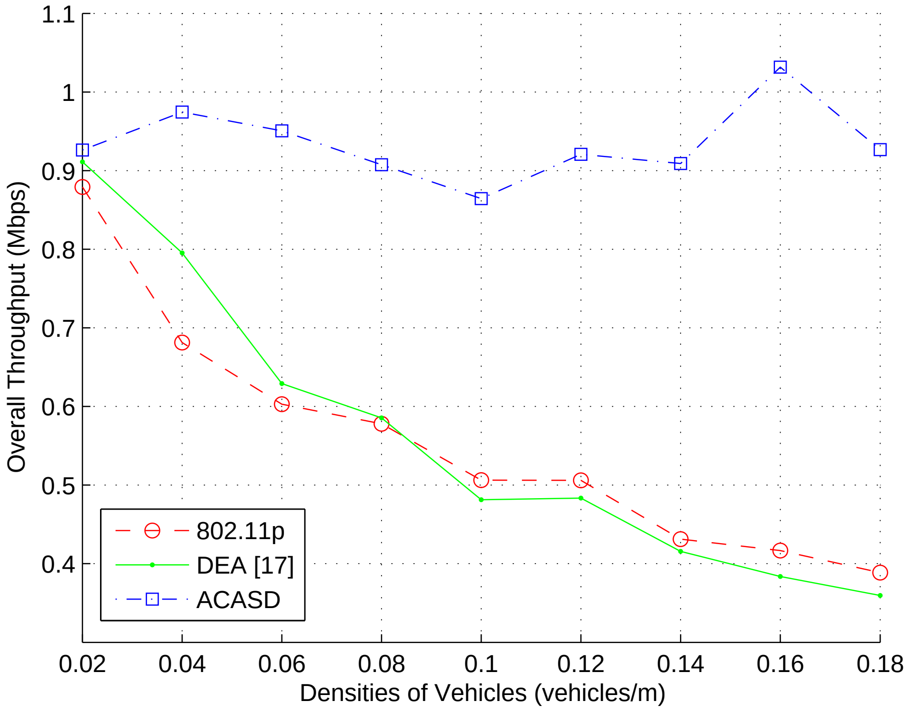


Figure 6.11: The overall throughput in the multi-service scenario.

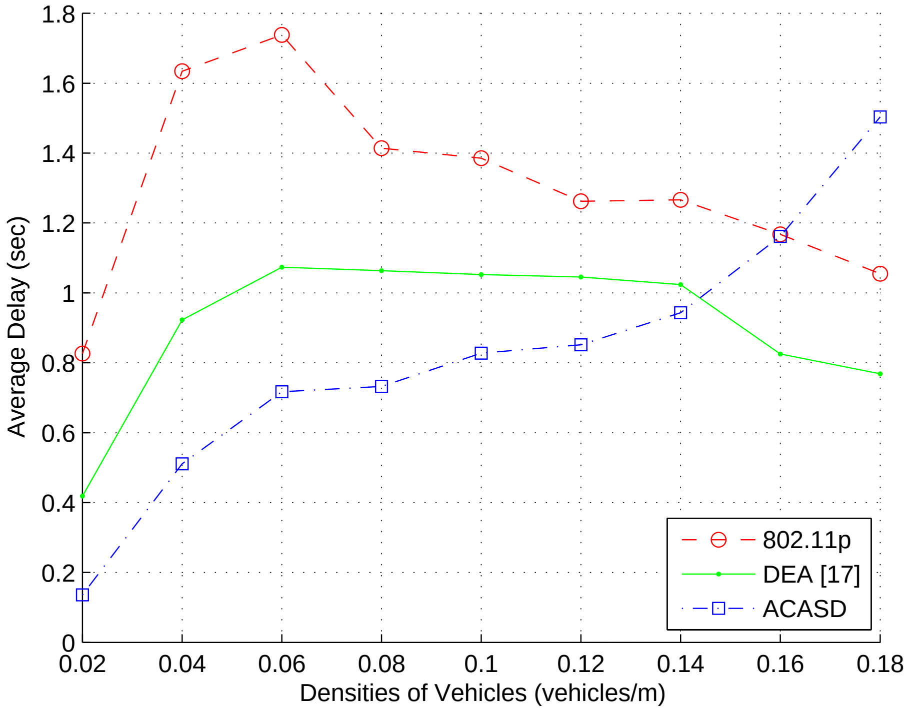


Figure 6.12: The average delay in the multi-service scenario.

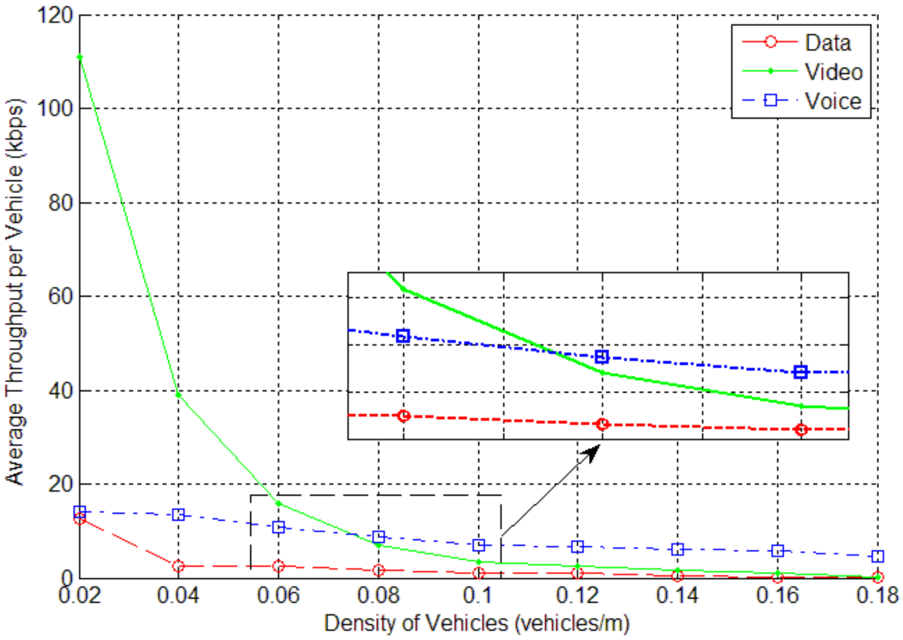


Figure 6.13: The average throughput per vehicle of different services in the multi-service scenario.

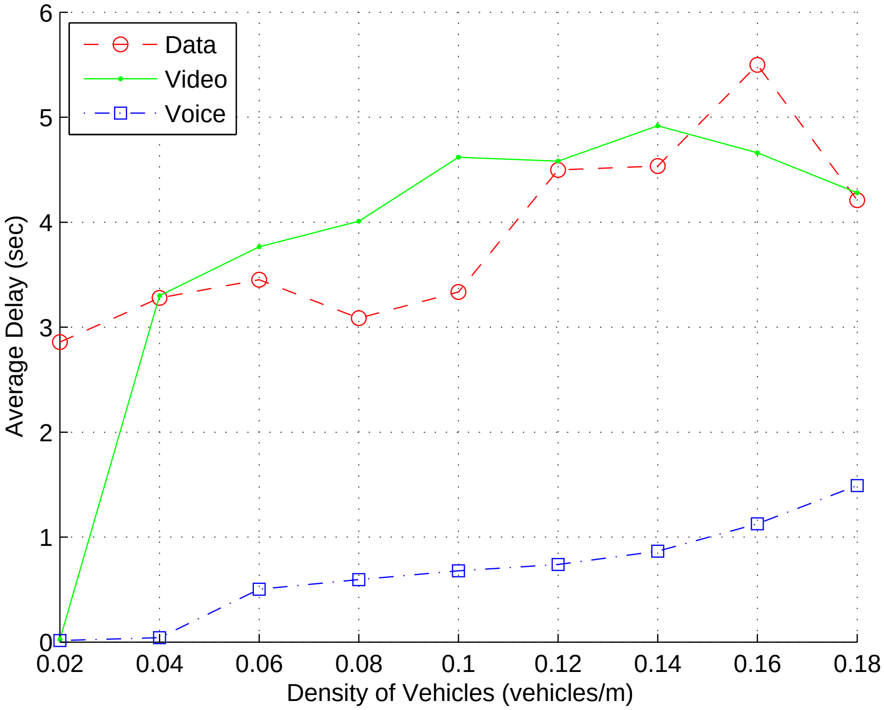


Figure 6.14: The average delay of different services in the multi-service scenario.

6.5 Results of Two Combined Schemes

In this section, the performance of combining the `ORAM` scheme and the `ACASD` scheme is investigated in the multi-service scenario. The combined case which includes both the `ORAM` scheme and the `ACASD` scheme is referred to as `CORAC`.

Fig. 6.15 and Fig. 6.16 compare the combined scheme `CORAC` with the two individual schemes. As seen, both the overall throughput and the overall delay of the combined scheme outperform the individual scheme alone. The overall access performance is guaranteed by the `CORAC` scheme.

To compare the performance of different services, the average throughput and the average delay of different services are shown in Fig. 6.17 and Fig. 6.18, respectively. As seen in Fig. 6.18, the delay of the VO traffic is the lowest among the three different services. Similarly, Fig. 6.17 shows that the throughput of the VO traffic always keeps at a high level across the entire vehicle density range. When the vehicle density increases, the throughput of the DA traffic decreases faster than that of the VI traffic. The delay of the DA traffic is always higher than that of the VI traffic. In the `CORAC` scheme, the traffic of different application operates in the order of the assigned priorities to first guarantee the QoS of the services with higher priorities. The results demonstrate that the `CORAC` scheme is effective in the multi-service scenario and the QoS requirements for different services can be satisfied.

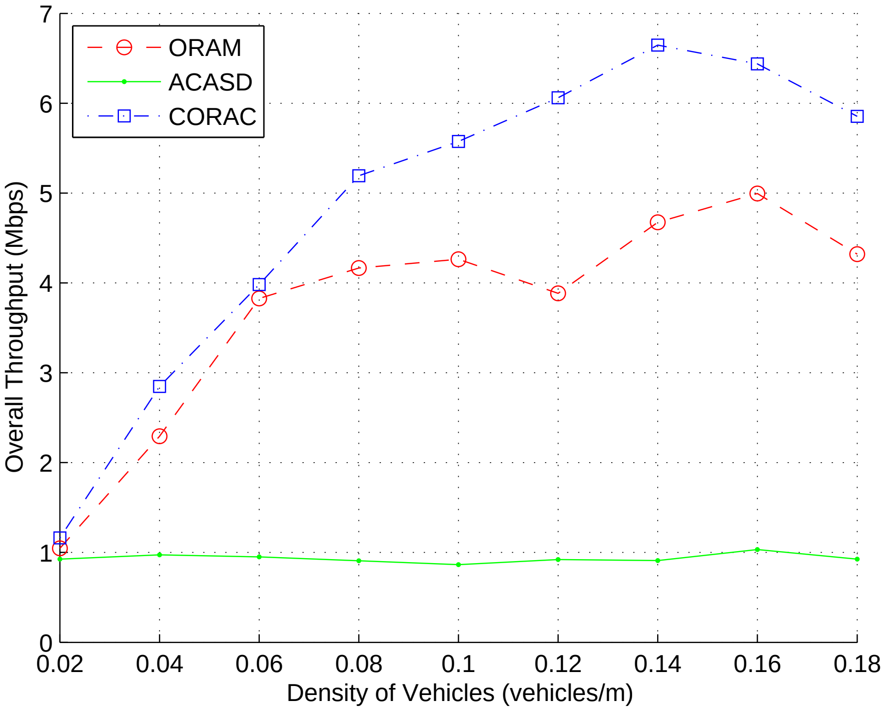


Figure 6.15: The overall throughput in the multi-service scenario.

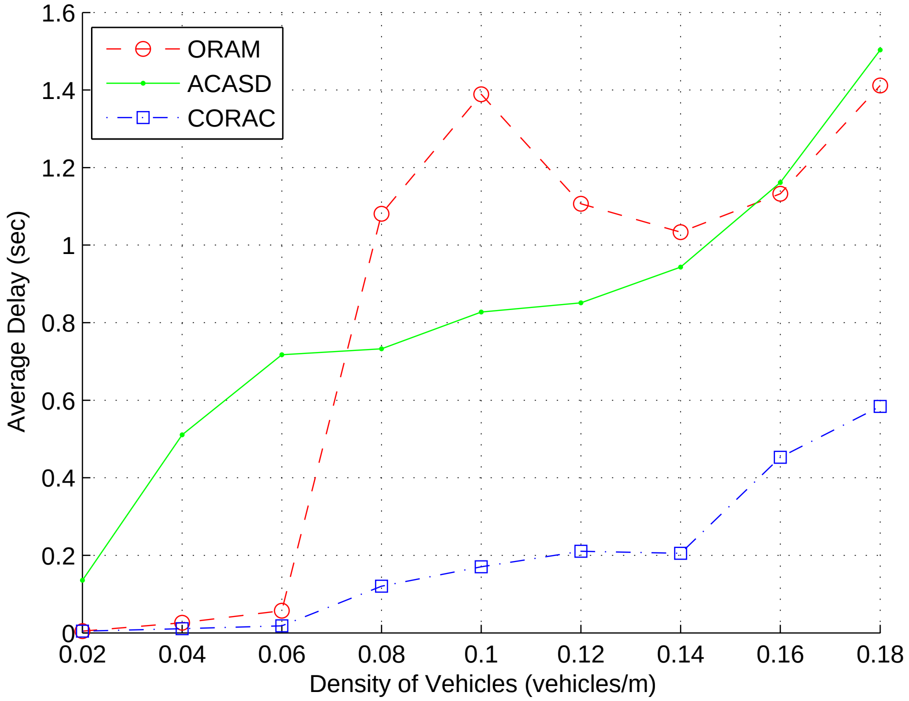


Figure 6.16: The average delay in the multi-service scenario.

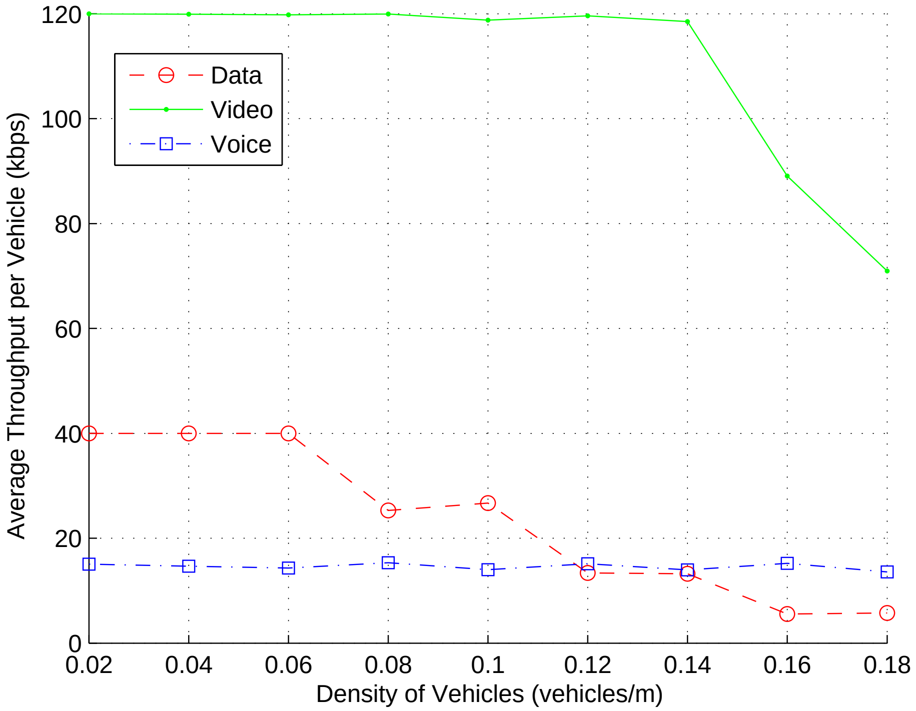


Figure 6.17: The average throughput of different services in the multi-service scenario.

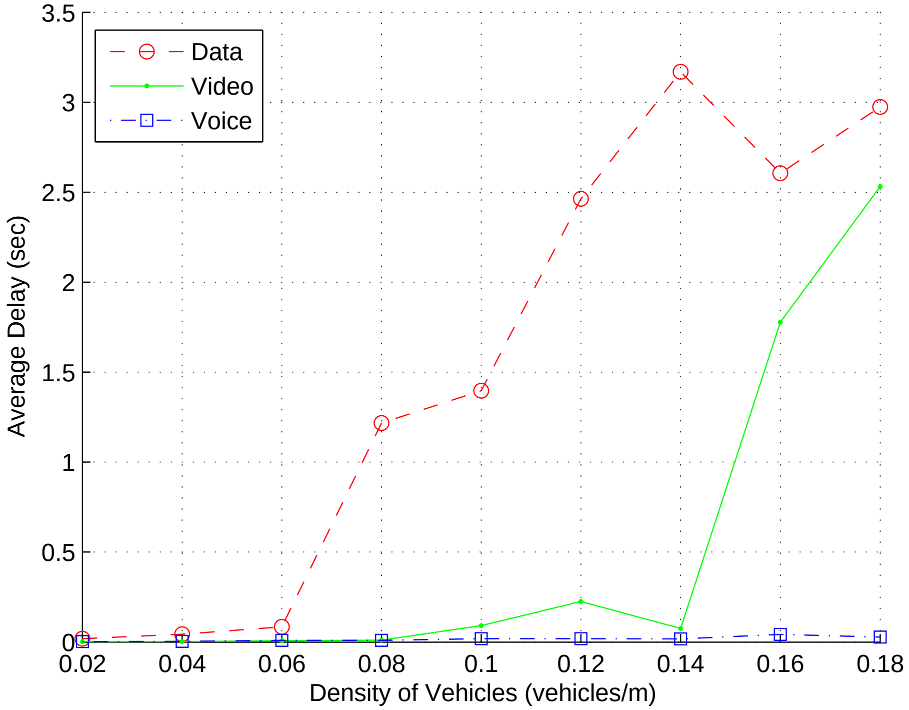


Figure 6.18: The average delay of different services in the multi-service scenario.

Chapter 7

Conclusion and Future Works

7.1 Conclusion

In this thesis, we proposed QoS enhancement solutions to support multiple services in drive-thru Internet. First, we proposed the opportunistic vehicle relay with adaptive modulation scheme (`ORAM`), for which theoretical analysis was also developed to validate its effectiveness. Furthermore, to avoid the unnecessary collisions and assign the appropriate priority for multiple services, we have proposed the adaptive collision avoidance with service differentiation scheme (`ACASD`), which is able to adjust the MAC layer parameters (contention window size) adaptively according to the current vehicular network environment.

The simulations that evaluated the performance of the proposed QoS enhancement schemes were conducted with our vehicular network simulator.

This simulator consists of three major modules, viz., the vehicle traffic model simulator, multi-service simulator and event-driven MAC layer simulator. We consider the FTM traffic model, which is the most commonly used one, to generate the trace file. Three types of applications (DA, VI, VO) are deployed in our simulation scenario. The vehicle users can choose the service type randomly but satisfy fixed percentages for DA, VI, and VO applications. The contention-based channel access mechanism of IEEE 802.11 MAC is also implemented in the event-driven MAC layer simulator to simulate the packet transmission and contention collisions. Different types of packets are delivered to the destination through direct or relay transmissions over the simulated MAC layer channel.

We first evaluate the performance of the `ORAM` scheme in the vehicular network simulator and compare it with some existing schemes. The simulation results of the uplink scenario show that the access performance of the `ORAM` scheme is much better than that of the other reference schemes. However, in a more realistic and complex multi-service scenario, the QoS of the `ORAM` scheme in the high vehicle density situations cannot be guaranteed. The low priority traffic (DA) even performs better than the high priority traffic (VI, VO) in the high density situations. This is because the inappropriate priority assignments for multiple services in the congested network lead to the undesired results that the low priority packets occupy more transmission time.

Then, we carried out the simulation of the `ACASD` scheme in the multi-service scenario. The simulation results demonstrate that multiple services with different priorities are able to perform appropriately according to their priority levels. However, in the saturated network, the QoS of the low-priority packets cannot be guaranteed the QoS performance because the packets of the high priority have more chances to access the channel.

We have also implemented the combined scheme which includes the `ORAM` scheme and the `ACASD` scheme in the simulation of the multi-service scenario. The simulation results show that QoS of the combined scheme performs better than that of each individual scheme. The QoS requirements of all traffic classes can be satisfied except that the traffic of the low priority is not able to meet the QoS requirement in the extremely high vehicle density situations.

7.2 Future Works

Our proposed schemes are able to capture the dynamic factors of the vehicular network and adjust the MAC layer parameters to satisfy the QoS requirements of multiple services. This work can be further extended in the following aspects.

Our simulator is able to generate the trace files of three traffic models (CSM, FTM, IDM). We consider only FTM in this thesis as it is widely accepted. We can also implement the other two traffic models in our simulation separately to see the effects of different traffic models on our proposed scheme.

We consider only one RSU that is deployed for one road segment in our study scenario. In the realistic environment, there can be multiple RSUs deployed along the road. Due to the mobility of the vehicles , a handoff strategy should also be implemented to deal with the handover from the current RSU to the next RSU. Particularly, the handoff strategy should satisfy the stringent QoS requirement of the voice application.

For the `ORAM` scheme, we only consider 6 modulation modes available for the RSU and vehicles to select. In some situations, the transmitter may not be able to choose the most appropriate modulation mode to achieve the best access performance. The scheme can be improved by increasing the number of modulation modes.

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