國立交通大學

網路工程研究所

碩 士 論 文

WAVE/DSRC 電子收費系統在預約區之分析與驗證

Analysis and evaluation on the reservation zone for WAVE/DSRC-based ETC system

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摘要

智慧型運輸系統(Intelligent Transportation System，簡稱 ITS)是整合資訊、通訊與管理等軟硬體設施之交通運輸系統，其能提升用路安全與交通服務之品質，而目前在高速公路所使用之電子收費系統(Electronic-Toll-Collection System，簡稱 ETC)亦是 ITS 中重要的應用之一，根據其架構之類型可區分成單一車道與多車道自由流，而後者架構之電子收費系統為目前世界各國發展之趨勢。在我們設計之 WAVE/DSRC 電子收費系統，其將通訊之區域細分成預約區與交易區，車輛進入預約區時會向控制頻道(Control Channel, CCH)發出預約之請求，一旦請求成功便會分配一服務頻道(Service Channel, SCH)給予車輛，並在進入交易區後使用該服務頻道完成交易扣款之程序。在本篇論文中，我們針對車輛在預約區能成功預約到頻道之機率做數學分析，並計算預約區長度與預約成功之機率。最後使用 Estinet 7.0 進行實驗模擬，並與我們已建立之數學模型做比對，結果顯示兩者之數據相當接近，以此佐證我們所提出的數學分析具有一定之準確性。

Analysis and evaluation on the reservation zone for WAVE/DSRC-based ETC system

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Abstract

Intelligent Transport System (ITS) is a traffic system which combines with information, communication, management, software and hardware devices, and the main purpose is to enhance the road-safety and quality of traffic service. One of important applications in ITS is Electronic Toll Collection (ETC). In accordance with the architectures, ETC system can be divided into two types, which are Single-Lane Free-Flow (SLFF) and Multi-Lanes Free-Flow (MLFF), and the latter architecture is the main worldwide trend for development.

In our proposed system, the ETC area is divided into reservation zone and transaction zone. A vehicle will send request message on control channel (CCH) when it enters reservation zone. Once the request message is sent successfully, then the system will allocate a service channel (SCH) to this vehicle. After that, the vehicle will use this SCH for transaction process. In the thesis, we propose a mathematical analysis for computing the probability that a vehicle reserves a CCH successfully. Finally, we conducted simulation experiments by Estinet 7.0 simulator to show the feasibility of the proposed ETC system. We also compared simulation results with the analysis results to show the correctness of the proposed mathematical model.

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Chapter 1
Introduction

Intelligent transport systems (ITS) is a traffic system which combines with information, communication, management, software and hardware devices, the main purpose of ITS is to provide real-time services for enhancing the transportation efficiency and improving the safety of drivers. There are many kinds of intelligent transport applications which are already implemented, such as emergency vehicle notification systems, automatic road enforcement, variable speed limits, collision avoidance systems, and dynamic traffic light sequence. High-way Electronic Toll Collection (ETC) system is also one of the most important applications in ITS. By ETC, vehicles are enabled to pay the charge via the communications between the Road-Side Unit (RSU) which is an infrastructure device and the On-Board Unit (OBU) which is a device installed on the vehicle when passing through the toll station. There are several advantages for adopting the ETC system on the high-way environment such as:

1. *Automatized transaction process*

The traditional method for transaction process needs human resources to operate and receive toll fees at toll stations, which is a large amount of expenses for the government; in contrast, ETC system has effectively resolved this kind of disadvantage. Through the wireless communication between devices, the transaction process can be automatically done.

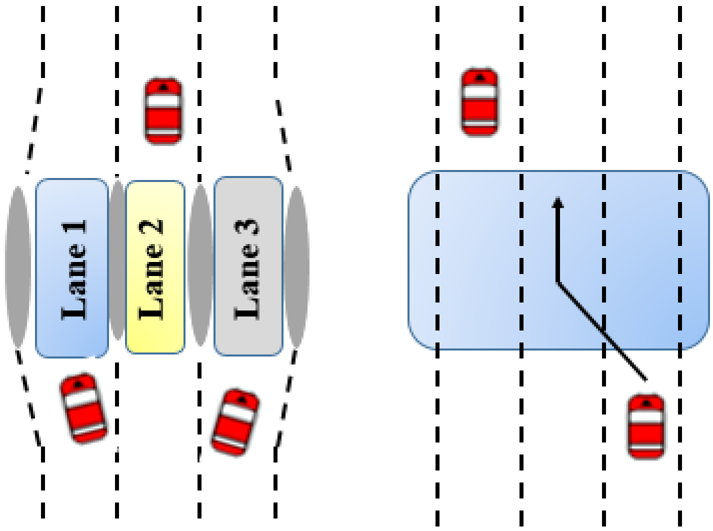
2. *Capability of energy-saving*

According to the recent research [1], the amount of air-pollution has significantly improved due to lower exhaust emission by enhancement of the driving speed of vehicle.

3. *Improve the traffic congestion problem*

Since the speed of a driving vehicle is higher with ETC system than with traditional toll collection, the traffic congestion problem is reduced so that the traveling time on the high-way will be lesser. According to the recent research [2] related to traffic transportation, in Taiwan, the traveling time from the most southern to the most northern location through the National High-way No.1 reduces 40 minutes in average as the ETC system is implemented.

In accordance with architectures implemented on ETC systems [3], they can distinguish into two types: single-lane free flow (SLFF) and multi-lane free flow (MLFF) shown in Figure 1-1. The common feature of SLFF and MLFF is that vehicles do not have to stop when passing through the toll station, the fee will be automatically charged through the transaction process between the devices. The different features are that in the SLFF ETC system, as shown in Figure 1-1 (a), since there are barriers set up between lanes, vehicles have to obey lower traveling speed regulated by the related authorities. This is because dangers may happen if vehicles drive through this zone with high speed. Besides, the vehicle cannot arbitrarily alternate the lanes due to these barriers. On the contrary, in the MLFF ETC system as shown in Figure 1-1 (b), vehicles do not have these two above-mentioned limitations.



(a)Single-lane free flow (b) Multi-lane free flow

Figure 1-1. Two types of ETC systems

However, MLFF ETC system has one disadvantage that should resolve, that is, since the traveling speed is high for a vehicle through the transaction area, the access delay is shorter than one with SLFF ETC system, which means that we need a stable wireless communication with high transmission rate and low latency to sustain the requirement of MLFF ETC system.

Our developed model of ETC system is based on MLFF architecture, with Dedicated Short-Range Communication / Wireless Access in Vehicular Environment (WAVE/DSRC) implemented as the wireless communication technology. The WAVE/DSRC technology consists of short to medium range wireless communication channels which is standardized by IEEE 802.11p and IEEE 1609 series, and it is suitable for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Besides, the WAVE/DSRC supports multi-channel operations defined in 1609.4, hence it can significantly reduce the delay for channel access so that immediate services can be provided. As a result, WAVE/DSRC is appropriate for MLFF ETC system since it has features such as scalable, robust, low-latency and high-throughput.

The other characteristic of our model is that, in the communicated area of the ETC system, we divide it into reservation zone (R-zone) and transaction zone (T-zone). A vehicle in the former zone has to contend channel access with other vehicles for getting successful channel reservation based on contention method, besides a vehicle that has reserved the channel has to wait for polling by RSU to complete the transaction process in the latter zone.

In this thesis, we will focus on the analysis of reservation probability in the R-zone. Notice that if the length of R-zone is too short, we might get the consequence that the reservation probability does not reach 100% and then the vehicle might fail to complete the transaction process. In contrast, if the length of R-zone is longer enough, the reservation probability will reach 100%, then the vehicle will absolutely complete the transaction process. After finishing analytical part, we will compare the analysis results with the simulation results, which is conducted by Estinet 7.0 simulator. We learn that the simulation results almost match analysis results, which implies the mathematical analysis model possess enough correctness.

The rest of this thesis is organized as follows. In chapter 2, we describe the architecture of the ETC system and WAVE/DSRC communication technology, in chapter 3, we will show the mathematical analysis of reservation ratio in the R-zone, in chapter 4, the experiment design and results are evaluated and discussed. Finally, we conclude this thesis in chapter 5.

Chapter 2

Related works

2.1 Wireless communication technologies

Most of the ETC systems that have been implemented in the world are based on the communication technology of DSRC [4]. DSRC is a radio frequency (RF) communication technology which is appropriate for the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, the main application of V2V is to exchange the safety message with each other, it has high real-time requirements, whereas V2I is based on that one of them is unable to move, such as automatic toll collection or to derive the information of parking lot. DSRC also provides the short to moderate range communication services such as public safety or private data transmission in the vehicular environment, it has transmission range from 300 to 1000m and data transmission rate from 3 to 27 Mbps, which is much better than other wireless communication medium such as microwave and infrared shown in Table 2-1.

Table 2-1. The comparison of current wireless communication technologies

Communication mode \ Assessment items		Transmission range	Transmission rate	Main application	Requirement of safety	Mobile ability	Real-time property
V2R	Microwave	10～50 m (depends on power)	10~100kbps	Electronic payment service (EPS)	High	Medium	Medium
	Infrared	10～50 m (line-of-sight)	10~100kbps	Electronic payment service (EPS)	High	Medium	Medium
	DSRC	WLAN: 300～1000 m	mobile: 3～27 Mbps	Dynamic/ Fixed point short-range data transmission	Medium	High	High

Notice that the allocated band for DSRC in every country does not completely equal. In 1999, the U.S. Federal Communication Commission (FCC) assigns 5.850~5.925GHz band for vehicular communication, within 75MHz bandwidth divided into 7 sub-channels, numbered 172, 174, so on till to 184. The channel number of 178 is called control channel (CCH), which is used for transmitting the safety-related emergency message; other 6 channels are called service channel (SCH), which support data transmission of general purpose, as shown in the Figure 2-1.

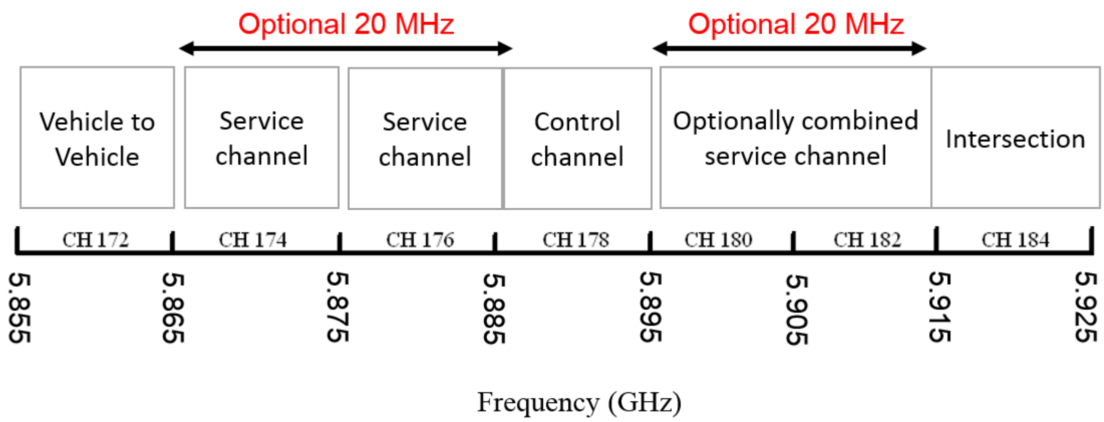


Figure 2-1 The DSRC band in the United States

The WAVE/DSRC technique adopt the IEEE 802.11p standard for the bottom layer with 1609 series standards for higher layer. In Figure 2-2, we see that the WAVE/DSRC protocol stack is corresponding to the OSI reference model.

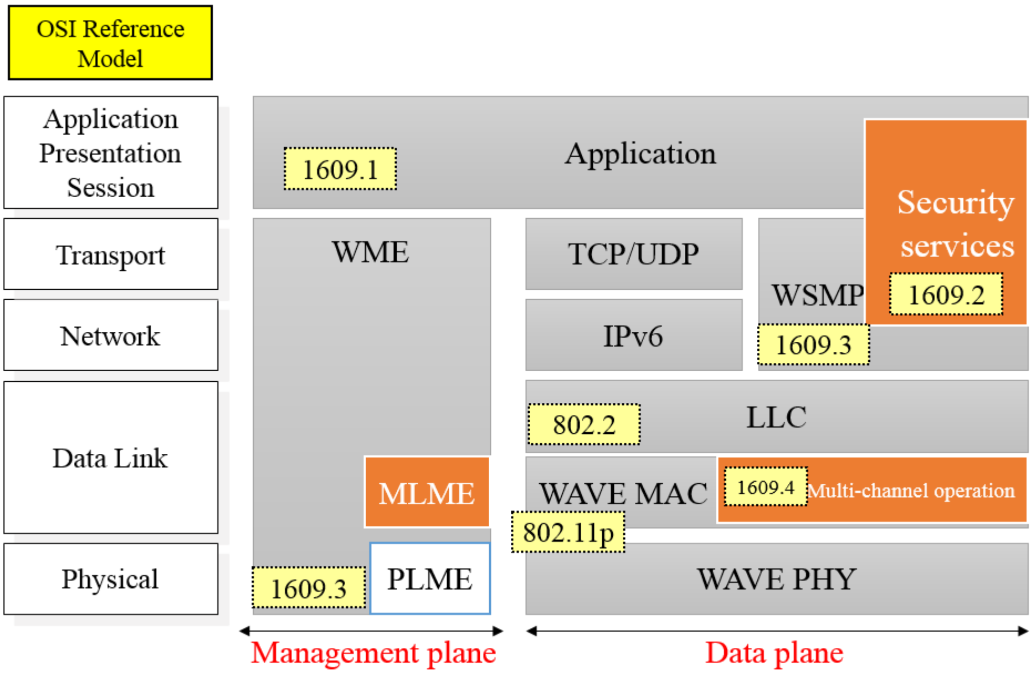


Figure 2-2 WAVE/DSRC system standard architecture

IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environment (WAVE). IEEE 1609.4 standard supplements the function and service of IEEE 802.11p MAC layer, that is, to provide multi-channel operation. The operation is consisted of channel routing, user priority, channel coordination, channel access and so on. IEEE 1609.3 standard specifies the protocols and services of network layer and transport layer, providing services of addressing and data delivery, so that the top-layer applications can access WAVE communication service to achieve the multi-channel operations between WAVE devices. IEEE 1609.2 provides security services for applications and management messages, since the security issues are the most concerned, the services provided by the application should have capability of defending eavesdrop, counterfeit and modification. IEEE 1609.1 is a resource manager, which describes the flow of the command-response interchange between multiple remote applications and the resource manager.

In this thesis, the main protocols that we concern about are 1609.4 and 802.11p standard, we will discuss about these two protocols in 2.2 and 2.3, respectively.

2.2 IEEE 1609.4 standard

As illustrated in Figure 2-3, IEEE [5] proposes a concept that the time is divided into alternating intervals, which are CCH interval (CCHI) and SCH interval (SCHI) with each persisting for 50ms. A pair of CCHI and SCHI form a Sync interval, which means there are 10 Sync intervals in one second. It's a straightforward thought that vehicle safety message rate is set as 10Hz since higher rate will result in too much waste time on switching the channel and lower rate will result in that vehicle safety is not guaranteed.

When the timing reaches the CCHI, the DSRC radio should be tuned to CCH to send or receive the safety-related message, once there is no any non-safety application communication in the SCHI, then the radio will continuously use the CCH. However, once there is any non-safety application communicated in SCHI, then the DSRC radio is used for safety communication during the CCHI and used for other commercial applications during the SCHI.

Notice that the standard further defines the guard interval at start of each interval, which is an interval used for channel switching and synchronization between WAVE devices. In general condition, the guard interval occupies 4~6 ms for each CCHI or SCHI.

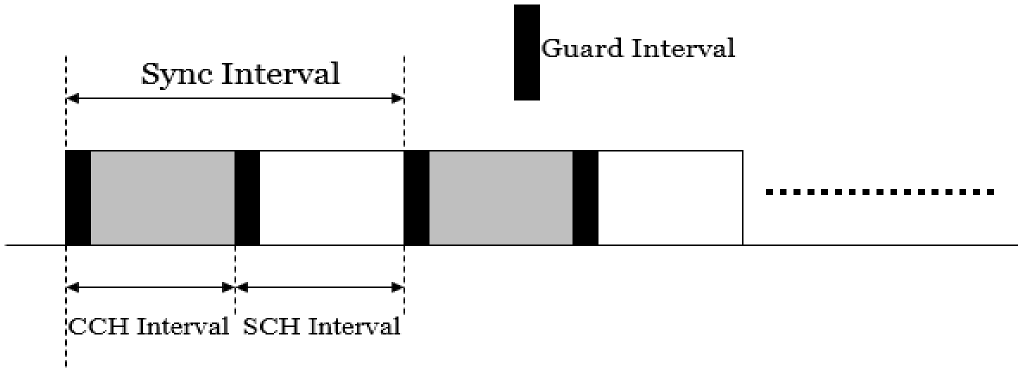


Figure 2-3 CCH, SCH, Guard and Sync intervals

2.3 IEEE 802.11p protocol

The IEEE [6][7][8][9][10][11] makes use of the PHY supplement 802.11a and the MAC layer QoS amendment from 802.11e. The Orthogonal frequency-division multiplexing (OFDM) utilized in the 802.11p PHY layer has an advantage that can cope with severe channel condition such as narrowband interference and frequency-selective fading due to multipath. In MAC layer, 802.11p will use the enhanced distributed channel access (EDCA) mechanism, which is an enhanced version of the distributed coordination function (DCF) from legacy 802.11 standard. EDCA uses carrier sensing multiple access with collision avoidance (CSMA/CA) protocol, CSMA/CA is used to detect the collision problem when packets transmit via wireless mediums. The brief procedure of CSMA/CA is described as follows. Initially, the node with transmitted data will detect the channel status, if the channel is idle for an arbitrary inter-frame space (AIFS) period, and a node is allowed to transmit only at the beginning of each slot time, in which defines as the time need for a node to detect the transmission of other nodes. This time slot includes the propagation delay, the time needed for a node to change from receiving state to transmitting state, and the time to signal to the MAC layer the state of the channel. After that, the back-off process will be initialized. In the back-off phase, the back-off counter will choose a value uniformly from 0 to contention window size, and begin to decrement whenever the channel is sensed idle, once the counter reaches 0, it will start to send the data. After all, if no ACK frame is sent back from the receiver to the sender, it means the data is lost or packet collision occurs, then the sender should retransmit the data; otherwise if the ACK frame is received by the sender, it means the data is transmitted successfully to the receiver. The more specific procedure of CSMA/CA protocol will be discussed in the next chapter.

We have to notice that in our implemented ETC system, since the range of transaction area is short and the transmitted range of vehicle (300m~1000m in DSRC spec) is large enough to cover with each other, it's not necessary for us to consider the hidden terminal problem, which implies that the Request to Send/Clear to Send (RTS/CTS) access mode will not be used in our ETC system scenario.

Since 802.11p extends the 802.11e EDCA QoS mechanism, different service classes are obtained by prioritizing the data traffic according to the corresponding access category (AC). There are four queues in MAC layer which implies that each node maintains four queues as illustrated in the Figure 2-4, with parameters that will be used in the queue are such as CW_{min}, CW_{max}, AIFSN and maximum transmit opportunity (TXOP).

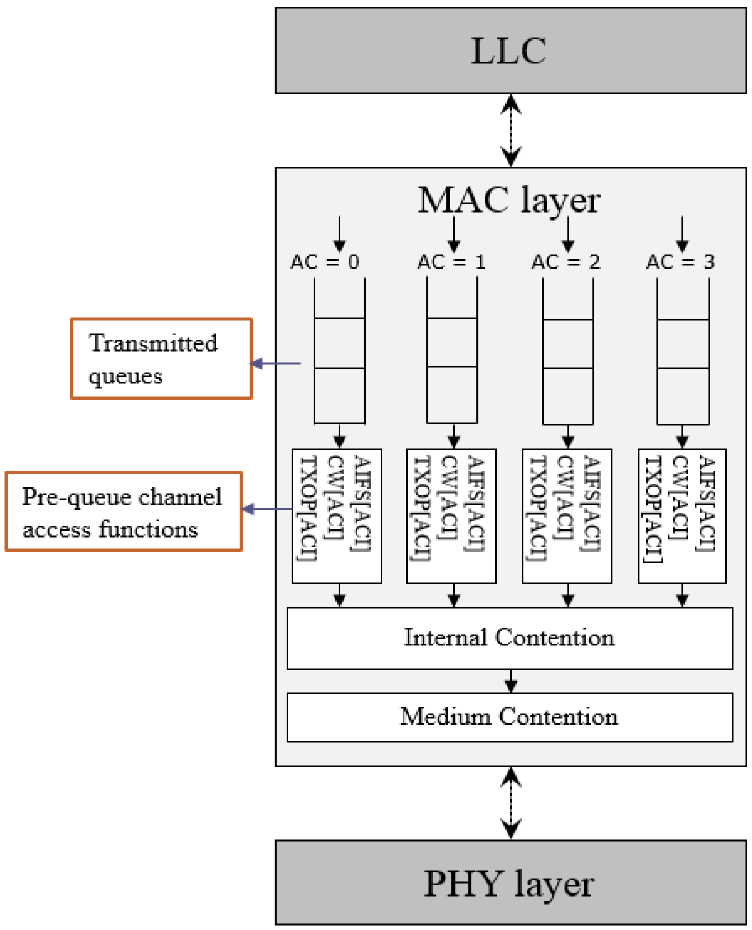


Figure 2-4. The contention between data packets and four queues in MAC layer

The transmitted data with higher priority such as real-time services, will have shorter waiting time in the queue since it has lower contention window size and shorter AIFS, besides, a station can send as many frames as possible in the defined TXOP period; in contrast, the transmitted data with lower priority will have longer waiting time, besides if the corresponding TXOP is 0, it's limited to transmit a single MAC service data unit (MSDU). Table 2-2 shows the default EDCA parameter for each AC.

Table 2-2. Default EDCA Parameters for each AC

AC	CW_{min}	CW_{max}	AIFSN	TXOP
Background (AC_BK)	15	1023	7	0
Best effort (AC_BE)	15	1023	3	0
Video (AC_VI)	7	15	2	3.008ms
Voice (AC_VO)	3	7	2	1.504ms
Legacy DCF	15	1023	2	0

2-4 ETC system architecture

ETC is an automatic toll charging method, which is usually used on the high-way, or on the chargeable tunnels and bridges, also is common for being implemented in the downtown since it can efficiently alleviate the traffic congestion problem in the metropolis area. The fundamental of ETC system is that, whenever a vehicle passes through the toll station, it can use the OBU install on the vehicle to communicate with RSU by the DSRC wireless technology. After all, it will automatically deduct the fee from the user account.

The advantages of implementing ETC system are that, vehicles which install OBU can complete transaction process in a short time without any necessary to prepare for cash or freeway toll tickets; also, it has some features such as energy saving, time saving and alleviation of traffic congestion originally resulted from manual toll collection. Besides, it’s allowable for ETC system to charge different values of fee in accordance with degrees of traffic congestion. Whenever the congestion is severe, the value of fee should be increased to disperse the traffic flow.

In recent years, many studies of ETC system have been proposed. In [12], the author mainly reviewed the research and development work of the ETC system, including the composition and principle of ETC system, the design of vehicle's automatic identify system and several major vehicles' identification technologies. In [13], the author proposes a MLFF ETC system which has a 6.2m height overhead gantry covering the width of the three lanes motorway, also this system has three antennas based on 5.8 GHz microwave link. In [14], the author proposes a very simple method for enhancing the performance of infrared ETC systems, using two typical low-cost commercial LEDs with different half-intensity angles. In [15], the author proposes a millimeter-wave MLFF ETC system that can simultaneously perform multi-target tracking using the pulse-Doppler radar technique and multi-data communication using the concept of frequency multiplexing in communication systems. In [16], the author proposes an effective method for implementing the enforcement that will be used in the MLFF ETC system.

The general architecture of the ETC system [17] contains two components: (a) Automatic Vehicle Identification and Transaction Processing (b) Violation Enforcement module, which is shown in the figure 2-5. The component of automatic vehicular identification and transaction processing involves RSU and OBUs, when vehicle enters the transmission range of RSU, the RSU will subjectively communicate with the OBU for exchanging information such as authentication and type of vehicles, then RSU will identify the vehicle type and eliminate the fee from its account. Finally, RSU will send the user information to back-end server for further handling of user account.

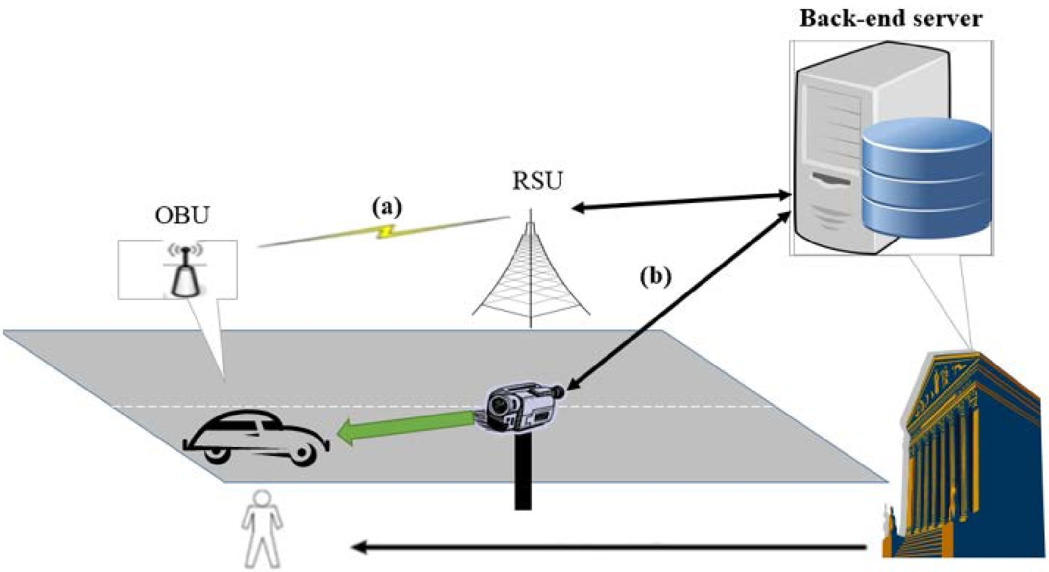


Figure 2-5 The ETC system architecture

However, if the vehicle does not install the OBU or the fund in the user account is not adequate, the module of violation enforcement will be initialized. The module of violation enforcement involves the digital camera and automatic license plate recognition (ALPR) technology, and the whole operation process is as follows. At beginning, the vehicle image will be derived by the digital camera, then ALPR will recognize the plate number of vehicle. Finally, the plate number information will send back to the back-end server for further pursue of bills.

Our proposed ETC system model is depicted in Figure 2-6. In our system, we divide the transaction area into reservation zone (R-zone) and transaction zone (T-zone), with the central controller contains with the channel allocator and the polling scheduler.

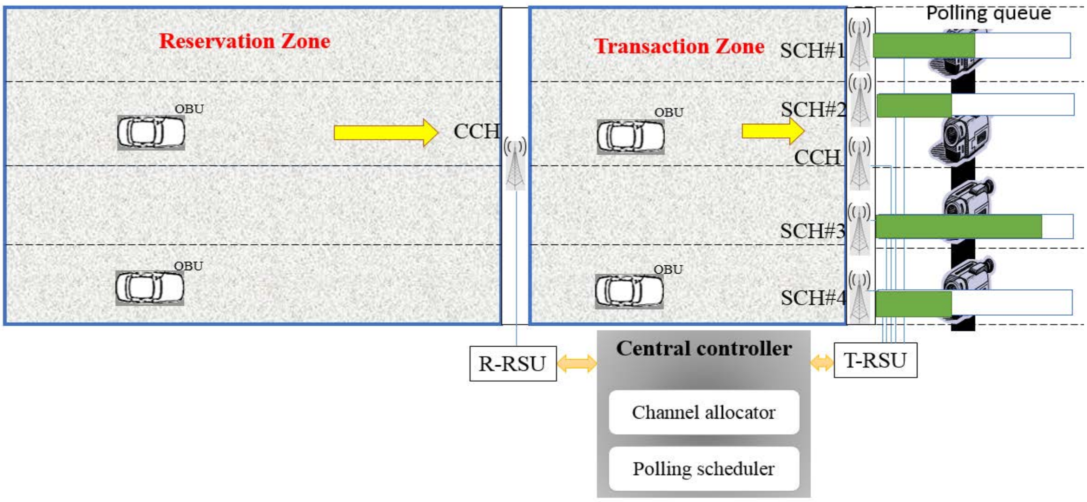


Figure 2-6. The architecture of our developed ETC system

The R-zone is contention-based with a Reservation-RSU (R-RSU) located at the end of area, the purpose for the R-zone is to let the vehicle get the reservation. Based on the channel access scheme of CSMA/CA defined in MAC protocol, once more than one vehicle intends to contend the channel access simultaneously, the reservation might fail resulted from the packet collision. Notice that if a vehicle does not get the channel access before leaving the R-zone, it has a high probability for the transaction process to be uncompleted, hence it's a critical issue for us to derive the channel reservation ratio of a vehicle. We will discuss about this issue in the next chapter.

The reservation process for a vehicle in R-zone will be described as follows. In CCHI, the R-RSU will periodically broadcast R-beacon frames for each 100ms on CCH, the information contained in the beacon frame are such as timestamp, beacon interval and capability information. When vehicles without channel-reserving receive the beacon message, it will send R-Request (R-REQ) frame to R-RSU on CCH, again we have to notice that there may have several vehicle attempting to send R-REQ packets to R-RSU at the same time, which will result in failure of contention due to packet collision as just mentioned. After R-RSU receives R-REQ frame, the channel allocator will choose a SCH whose polling queue has the smallest number of un-polled vehicles, the reason for doing so is because of load balancing considerations. When the allocation is done, R-RSU will send back an R-Request (R-REQ) frame, as the vehicle receives the R-REQ message will it tune the SCH to corresponding SCH number and again sends an ACK frame back to R-RSU. At final, R-RSU will add this vehicle to the corresponding polling queue of T-RSU to complete the channel reservation. The packet flow of channel reservation is shown in figure 2-7.

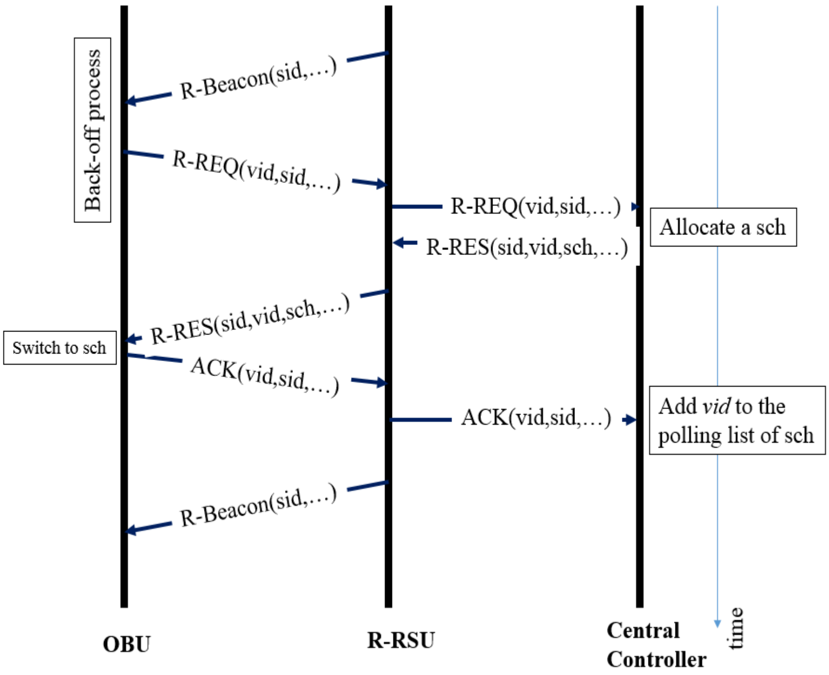


Figure 2-7 Packet flow of channel reservation process

The T-zone is contention-free based with five T-RSUs installed at the end of the area, within one of T-RSUs tuned on CCH, while others poll on SCHs. For a vehicle in T-zone, each T-RSU except the one tuned on CCH, will poll this vehicle on SCH for transaction process, which is based on the operating mechanism of point coordination function (PCF) defined in MAC protocol, that is, these T-RSUs will be the point coordinators (PC) for vehicles. In addition, the T-RSU which tuned on CCH is used to serve vehicles which are failed to reserve the channel before leaving the R-zone.

The transaction process for a vehicle in T-zone will be described as the follows. The T-RSU will poll the reserved vehicle as this vehicle is in the T-zone, after vehicles receive the polling frame, they will send back an ACK frame to the corresponding T-RSU based on their own SCH number on SCH. The transaction process is completed when T-RSU receives the ACK packet polled from the vehicle. Notice that the T-RSU will prior to poll the vehicle which has minimum remaining time on T-zone, using the method of earliest deadline first (EDF).

If vehicles cannot reserve channel successfully before leaving the R-zone, the T-RSU which tuned on CCH will use contention-based access scheme to help this vehicle to reserve channel, and use three-way handshake method to complete the whole transaction process. Finally, the flow chart of channel reservation and transaction process is shown in Figure 2-8.

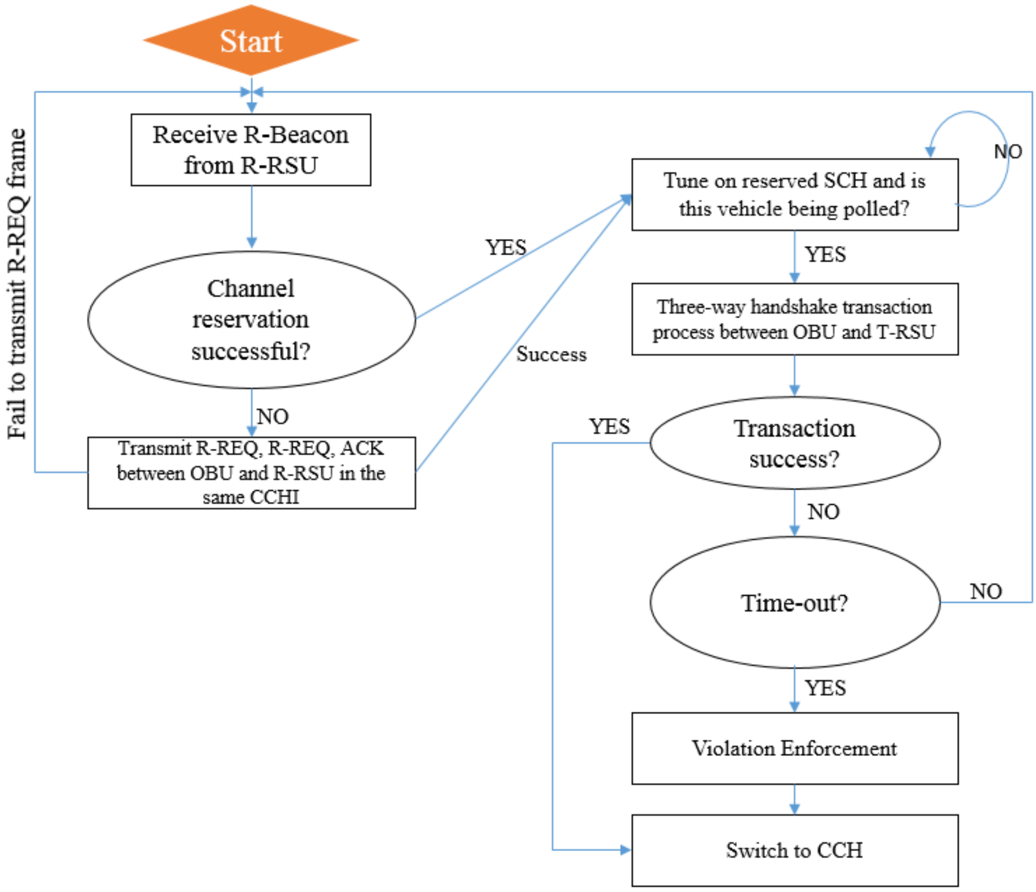


Figure 2-8 Flow chart of channel reservation and transaction process

Chapter 3

Mathematical analysis

In this chapter, we will analyze the successful reservation probability of the R-zone with different parameters, such as the length of reservation zone, vehicle arrival rate and average speed of the vehicle. Under our analysis method, the explicit reservation probability with varied length from entrance of R-zone can be estimated. The remained sections in this chapter will show the top-down approach of the analyzed process.

3.1 Overview of the analysis

Our main objective is to derive the successful reservation probability for a vehicle with different entrance distance. Here, we donate $f(d)$ as the successful reservation probability of a vehicle with distance *d* from entrance, where *d* is a real value which is between 0 to the length of reservation zone, and normally uses meters as its unit. As a straightforward thought, a vehicle will get the channel access in the first contention, or in the second contention, even worse in the afterward contentions, hence $f(d)$ can be expressed as following:

$$f(d) = g(1) + \big(1 - g(1)\big) \times g(2) + \cdots + \big(1 - g(1)\big) \times \big(1 - g(2)\big) \times \ldots \times (1 - g(r(d) - 1)) \times g(r(d))$$

$$= \sum_{i=1}^{r(d)} \Big(\prod_{j=1}^{i-1} \big(1 - g(j)\big) g(i)\Big) \qquad (1)$$

The parameters used in this function, including $g(i)$ and $r(d)$, are represented as the successful probability for i-th channel access and the maximum times of contentions for a vehicle (or the maximum transmission times of the R-REQ sent by a vehicle) with distance d, respectively. Figure 3-1 illustrates the schematic graph for vehicle to reserve the channel.

In the following sections 3.2-3.4, we will analyze the calculation methods of $r(d)$ and $g(i)$ step by step.

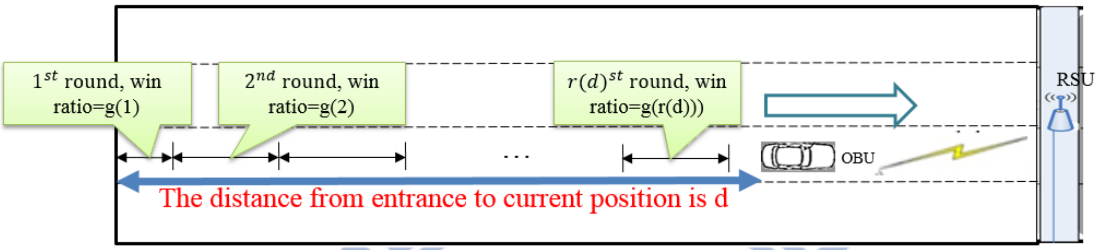


Figure 3-1 Overview of the reservation process for a vehicle

3.2 The analytical steps for transmission times

In the analysis of $r(d)$, we will introduce two parameters $h_c(i)$ and $h_s(i)$ at first. The former one $h_c(i)$ is vehicle displacement for the i-th contention that has been in failure, and the latter one $h_s(i)$ is the vehicle displacement for the i-th contention that has been in success. If a vehicle intends to reserve channel successfully by distance d, it must at least get the channel successfully in the last contention, in which means the last time for this vehicle to contend the channel access within distance d. This also indicates that, this vehicle losses all contentions before the last successful contention. Through the schematic diagram shown in the figure 3-2, we will clearly understand the architecture of the analysis.

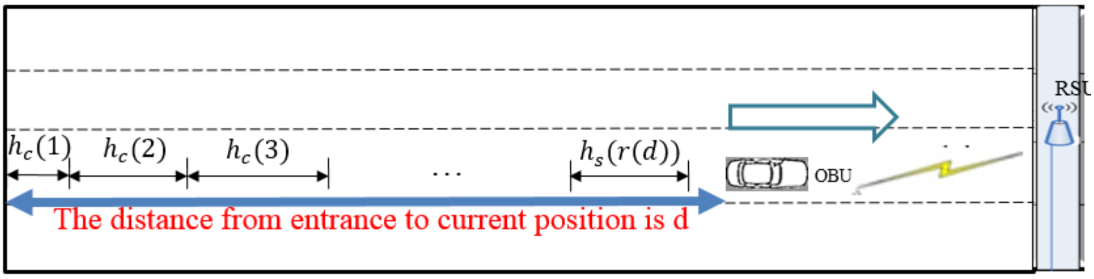


Figure 3-2. The schematic diagram of the system model

Hence, $r(d)$ can be computed as follows. If there exists a real positive integer α that satisfies $h_c(1) + h_c(2) + \cdots + h_c(\alpha - 1) + h_s(\alpha) < d$ and $h_c(1) + h_c(2) + \cdots + h_c(\alpha) + h_s(\alpha + 1) > d$, then the maximum contention times $r(d)$ is equal to α. Formally, it can be expressed as:

$$\exists \alpha \in N \ s.t. \sum_{i=1}^{\alpha-1} h_c(i) + h_s(\alpha) < d \ and \ \sum_{i=1}^{\alpha} h_c(i) + h_s(\alpha+1) > d,$$

$$r(d) = \alpha \qquad (2)$$

From a kinematic formula $\Delta x = v \cdot \Delta t$, where Δx represents the displacement, v represents vehicle speed and Δt represents spent time. Hence $h_c(i)$ can be expressed as $h_c(i) = v \cdot T_c(i)$ and $h_s(i)$ can be expressed as $h_s(i) = v \cdot T_s(i)$. Assume that the vehicle speed is a constant, so in the rest of this section, there are only two parameters that we have to estimate, which are failed transmission time $T_c(i)$ due to packet collision and successful transmission time $T_s(i)$, respectively.

In the IEEE 802.11 series standards, the channel access delay for a node to transmit the data is based on CSMA/CA mechanism defined in MAC protocol and is composed of the following three components: the medium access time after a busy medium, back-off delay before channel access and data transmission delay.

1. The medium access time after a busy medium: When a node attempts to access the channel, it has to detect the current channel status through executing the function of clear channel assessment (CCA) to detect whether the channel is in idle or busy condition. If the channel is in idle status, it can immediately access the channel after waiting for a period; on the other hand, if the channel is in busy condition, which means there is one of other nodes using the channel, it has to wait for the channel to become idle, then also have to wait for a period to begin the back-off procedure. Since the contention-based mechanism in the MAC layer of WAVE/DSRC follows 802.11e EDCA, the period can be expressed as:

$$AIFS[AC] = SIFS + aSlotTime \times AIFSN[AC] \quad (3)$$

   The AIFS means “arbitrary inter-frame space”, this parameter is similar to the DIFS of legacy DCF of IEEE 802.11 standard, but due to several priority levels in the EDCA, it has different values of AIFS according to the selected access category (AC).

2. Back-off delay before channel access: When a node begins a back-off procedure, it will uniformly select a random value between 0 to CW-1, where CW is the current contention window (CW) size. After that, it begins the back-off process within the value decremented, once the back-off counter reaches 0, the node will start to transmit the data. We have to notice that the CW size is not a fixed constant, as the node begins to transmit data without any retransmission, the CW size will be set as the minimum of contention window (generally donated as CW_{min}), as the retransmission occurs, the CW size will be doubled until reaching the maximum of contention window (generally donated as CW_{max}), when the CW size

reaches CW_{max}, it will stop to increment. In the regulation of 802.11 series, every packet can be retransmitted by a node with limited times, known as *Station Short Retry Limit (SSRL)*, once the packet has been retransmitted with limited times, the packet should be dropped, within the CW size reset to CW_{min}, then the packet is allowed to rejoin the contention of channel access. The whole process is known as *binary exponential back-off mechanism*.

3. Data transmission delay: In the initiation of this phase, a vehicle will send *R-REQ* message to the R-RSU, after that, there will have two possible cases, which are failed transmission and successful transmission, respectively. For the former case, if the vehicle does not receive the *R-RES* message sent from the R-RSU for a DIFS period, it means that the collision occurs during the data transmission. In this kind of situation, the *R-REQ* message sent from vehicles should be retransmitted; for the latter case, if *R-REQ* message has been successfully received by the R-RSU, the R-RSU will send *R-RES* message to the vehicle after a SIFS period. Again the vehicle will send an *ACK* message back to the R-RSU, so that R-RSU can confirm the connectivity between them is in a good status, and the channel allocator will add this vehicle to the corresponding polling queue of SCH. After all, the channel reservation process is completely done.

Figure 3-3 shows the IEEE 802.11e EDCA basic access mechanism, the steps for channel access are the same as the previously mentioned three components.

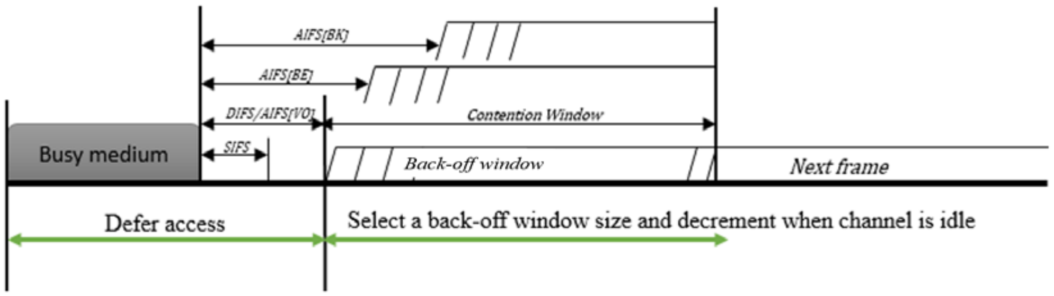


Figure 3-3. The IEEE 802.11e EDCA basic access mechanism

Now, we can derive the formulas of $T_c(i)$ and $T_s(i)$. These two functions can be expressed as the following:

$$T_c(i) = AIFS[AC] + \frac{CW(i \, mod \, M) - 1}{2} \cdot \left[\left(1 - p_{fr}(i)\right) \cdot aSlotTime + p_{fr}(i) \cdot d_{size} \right] + \frac{R}{D} + DIFS + \delta \quad (4)$$

$$T_s(i) = AIFS[AC] + \frac{CW(i \, mod \, M) - 1}{2} \cdot \left[\left(1 - p_{fr}(i)\right) \cdot aSlotTime + p_{fr}(i) \cdot d_{size} \right] + \frac{3R}{D} + 2 \times SIFS + 2 \times \delta \quad (5)$$

In $T_c(i)$ and $T_s(i)$, D stands for data rate, R stands for frame size, δ stands for propagation delay, and $p_{fr}(i)$ stands for the freezing probability for the back-off counter of i-th contention. In addition, $CW(i)$ and d_{size} will be explained as follows:

- $CW(i)$: The contention window size might have a variation as the retransmission occurs, in the following equation, the parameter of m represents the number of times which CW size increments from CW_{min} to CW_{max}, and M represents the maximum retransmission limit. Hence we express $CW(i)$ as:

$$CW(i) = \begin{cases} 2^i \cdot (CW_{min} + 1) \; for \; 0 \le i \le m \\ 2^m \cdot (CW_{min} + 1) for \; m < i \le M \end{cases}, \mathrm{m} = \log_2 \frac{CW_{max}+1}{CW_{min}+1}, \; M: SSRL \quad (6)$$

- d_{size}: Every time the back-off counter decrements, the node will continuously detect the channel status, if the channel is staying in idle state, then the back-off counter will keep decrementing; in contrast, if the channel is changed into busy state, the back-off counter will cease to decrement, waiting for the completion of data transmission from other nodes, then the back-off counter will restore to the decremented process. Here, the probability that the back-off counter will cease to decrement due to channel states changes into busy is called "frozen probability", we donate it as a function $p_{fr}(i)$, and the delay of data transmission by other nodes is donated as a function d_{size}. Thus, d_{size} can be expressed as:

$$d_{size} = \frac{3R}{D} + 2 \cdot SIFS + 2 \cdot \delta \tag{7}$$

3.3 The Markov chain model

Before conducting the successful probability of channel contention, we utilize the Markov chain model to describe the process of contending channel at first.

We consider a scenario that there are always *n* stations contending for the channel access, which means once a frame is successfully transmitted by a station, there will have another frame which waits for being transmitted, immediately. We give that $b(t)$ be the back-off window size at random time t in the process of channel contention, and $s(t)$ be the back-off stage *(0,1,…,M)* at random time t, where M stands for station short retry limit (SSRL).

When the back-off counter reaches 0, a station will send out the frame. However, if there are other stations transmitting the data at the same time, then the packet collision will occur, and we donate p as the collision probability. If we donate $[\mathrm{s(t)}, \mathrm{b(t)}]$ as the status of channel contention, then the process of channel contention will be a discrete Markov-chain which is shown in the Figure 3-4, with the one-step transition probabilities as follows:

$$\begin{cases} P\{i,k|i,k+1\} = 1 - p_{fr} & k \in (0, cw(i)-2); i \in (0, M) \\ P\{0,k|i,0\} = \dfrac{1}{cw(0)} & k \in (0, cw(0)-1); i \in (0, M) \\ P\{i,k|i-1,0\} = \dfrac{p}{cw(i)} & k \in (0, cw(i)-1), i \in (1, M) \end{cases} \quad (8)$$

Among which: (1) The decrement of the back-off time counter; (2) After a packet is transmitted successfully at stage i, a new packet begins with back-off stage 0; 3) After a packet is transmitted unsuccessfully at back-off stage i, the back-off interval is uniformly chosen in the range $(0, \mathrm{cw(i+1)})$.

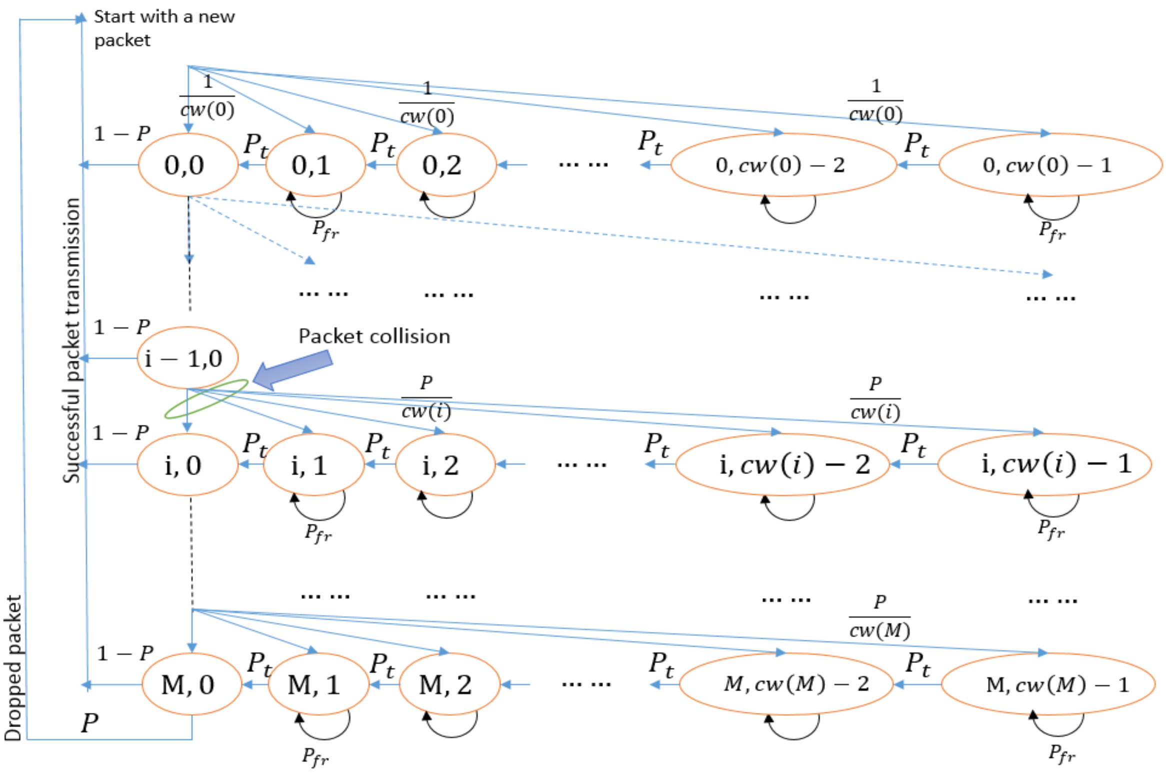


Figure 3-4. The Markov chain model for the back-off window size

Let $b_{i,j} = \lim_{t\to\infty} \mathrm{P}\{s(t) = i, b(t) = j\}$ be the stationary distribution of the chain. Owing to the chain regularities, the following relations hold:

$$b_{i,0} = p^i \cdot b_{0,0} \;\; for \; 0 \le i \le M \tag{9}$$

$$b_{i,j} = \frac{cw(i) - j}{cw(i)} \cdot \frac{1}{1 - p_{fr}} b_{i,0} \; for \; 0 \le i \le M, 1 \le j \le cw(i) - 1 \tag{10}$$

Equation (9) derives from that, when retransmission occurs i-times for a packet which has never transmitted yet, the state will transit from the stage 0 to the stage i in the Markov chain model, since the retransmission probability is p, the probability of consecutive i-times retransmission is p^i, hence we get the consequence of equation (10).

Besides, equation (10) derives from that, let's focus on the most right state $(i, cw(i) - 1)$ shown in figure 3-5 at first, since the transition probability from $(i-1, 0)$ to $(i, cw(i) - 1)$ will equal to the transition probability from $(i, cw(i) - 1)$ to $(i, cw(i) - 2)$, hence we get the following result:

$$\frac{p}{cw(i)} \times b_{i-1,0} = (1 - p_{fr}) \times b_{i,cw(i)-1} => b_{i,cw(i)-1} = \frac{1}{(1 - p_{fr})} \cdot \frac{p}{cw(i)} \cdot b_{i-1,0}$$

Moreover, let's focus on the $(i, cw(i) - 2)$ state, since the summation of transition probability from $(i-1, 0)$ to $(i, cw(i) - 2)$ and from $(i, cw(i) - 1)$ to $(i, cw(i) - 2)$ will equal to the transition probability from $(i, cw(i) - 2)$ to $(i, cw(i) - 3)$, hence we get the following result:

$$\frac{p}{cw(i)} \times b_{i-1,0} + (1 - p_{fr}) \times b_{i,cw(i)-1} = (1 - p_{fr}) \times b_{i,cw(i)-2} => b_{i,cw(i)-2} = \frac{1}{(1 - p_{fr})} \cdot \frac{2p}{cw(i)} \cdot b_{i-1,0}$$

Use the similar way, we get the consequence of equation (10).

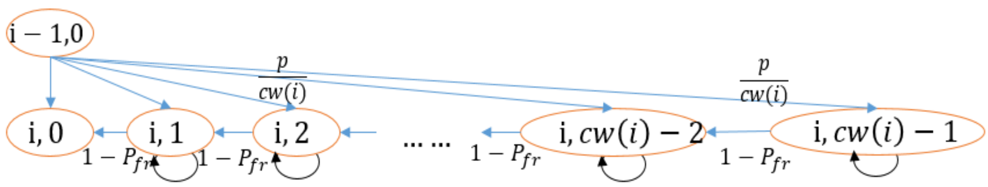


Figure 3-5. Equation (11) schematic diagram

The value of $b_{0,0}$ is determined by imposing the normalization condition

$$\sum_{i=0}^{m}\sum_{j=0}^{cw(i)-1} b_{i,j} + \sum_{i=m}^{M}\sum_{j=0}^{cw(i)-1} b_{i,j} = 1 \tag{11}$$

From equation (11), we can obtain

$$b_{0,0} = \frac{2(1-p)(1-2p)(1-p_f)}{(1-p^{m+1})(1-2p)+cw(0)(1-p)(1-(2p)^{m+1})+(2^m \cdot cw(0)+1)p^{m+1}(1-p^{(M-m)})(1-2p)} \tag{12}$$

Let τ be the probability that a station transmits in a generic slot time. As any transmission occurs when the back-off window is equal to zero, regardless of the back-off stage, it is

$$\tau = \sum_{i=0}^{M} p^i \cdot b_{0,0} = \frac{1-p^{M+1}}{1-p} \cdot b_{0,0} \tag{13}$$

To estimate the probability p that a transmitted packet collides, note that p is the probability that, in a time slot, at least one of the $n-1$ remaining stations transmits

$$p = 1 - (1-\tau)^{n-1} \tag{14}$$

To eventually compute the freezing probability p_{fr} that a decremented back-off counter freezes, note that p_{fr} is also the probability that, in a time slot, at least one of the remaining stations transmits

$$p_{fr} = 1 - (1-\tau)^{n-1} \tag{15}$$

Now, we have to use mathematical analysis method to evaluate collision probability p. Since we have already the equation (14) and (15), we can use equation (15) to replace τ in equation (14), and get the result as follows:

$$p - 1 + \left(1 - \frac{1-p^{M+1}}{1-p} \cdot b_{0,0}\right)^{n-1} = 0 \tag{16}$$

We define a function $s\big(p, n, M, m, cw(0)\big)$ with five parameters as

$$s\big(p, n, M, m, cw(0)\big) = p - 1 + \left(1 - \frac{1-p^{M+1}}{1-p} \cdot b_{0,0}\right)^{n-1} \tag{17}$$

where the number of contending nodes n, the maximum retry limit M, the doubled times of contention window size m, and minimum contention window size $cw(0)$ are already given, hence we only have to use a program for analysis to derive the collision probability p which satisfies $s(p, n, M, m, cw(0)) = 0$.

Most of the related works that utilize the Markov chain models for analyzing the back-off window are under saturation condition, which means that there are always n stations contending for the channel access. However, in our ETC system architecture, once a vehicle gets the channel access, it will not contend the channel again. That is, if there are n vehicles within the given distance d, among which there are possibly $n - k$ vehicles get the channel successfully with other k vehicles still have to contend the channel afterward. Hence if there are n vehicles within the distance d, the only thing that we have to undertake at first is to estimate k, which is the actual number of vehicles that have to contend the channel.

3.4 The analyzed process of successful reservation ratio

Figure 3-6 shows an R-zone environment with the following four variables:

1. λ: vehicle arrival rate for each lane
2. N_l: the number of lanes
3. v: the average speed of vehicles
4. l_R: the length of R-zone

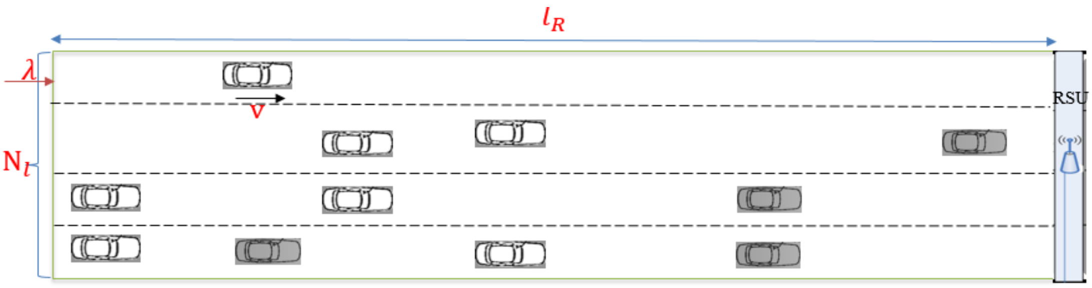


Figure 3-6, the R-zone environment with four important variables

The estimating process of the actual number of contending vehicles will be given as follows: We separate the R-zone into several sub-zones, and a vehicle will go through the sub-zone 1 of R-zone (we donate it as the first stage) to the sub-zone 2 of R-zone (second stage), and so on. Assume there are α number of vehicles entering the sub-zone 1 of R-zone at the initial stage, after the channel contention, these α number of vehicles will enter in the sub-zone 2, with some of which do not successfully get the channel reservation; meanwhile, there will have a number of new vehicles entering the sub-zone 1 of R-zone, then contend the channel with the previously vehicles that have not get the channel reservation successfully yet. These α vehicles will go through the sub-zone 3 of R-zone, to the sub-zone 4 of R-zone, and so on till leaving the R-zone (our objective is to let α reduce to 0, that is, these α number of vehicles can contend the channel successfully). When the system operates for a while, the actual number of vehicle in contention on the R-zone will gradually approach to a constant k, which is the number of vehicles that have to contend the channel.

There are four parameters that will be used in the process for analyzing the successful reservation ratio, named $n(i,j)$, α, $N(i)$ and $p_c(n,cw)$. The first one $n(i,j)$, is to calculate the expected value of contending vehicle of the j-th sub-zone in the i-th stage, as shown in the figure 3-7. The second one α, is the number of contending vehicle at the initial stage. The third one $N(i)$, is the total number of contending vehicles of i-th stage. Finally, the fourth one $p_c(n,cw)$, is the packet collision probability under the condition of n number of contending vehicles and the contention window size is cw, and the solution set is $\{p|s(p,n,1,0,cw) = 0, 0 < p < 1 \text{ and } p \in R\}$

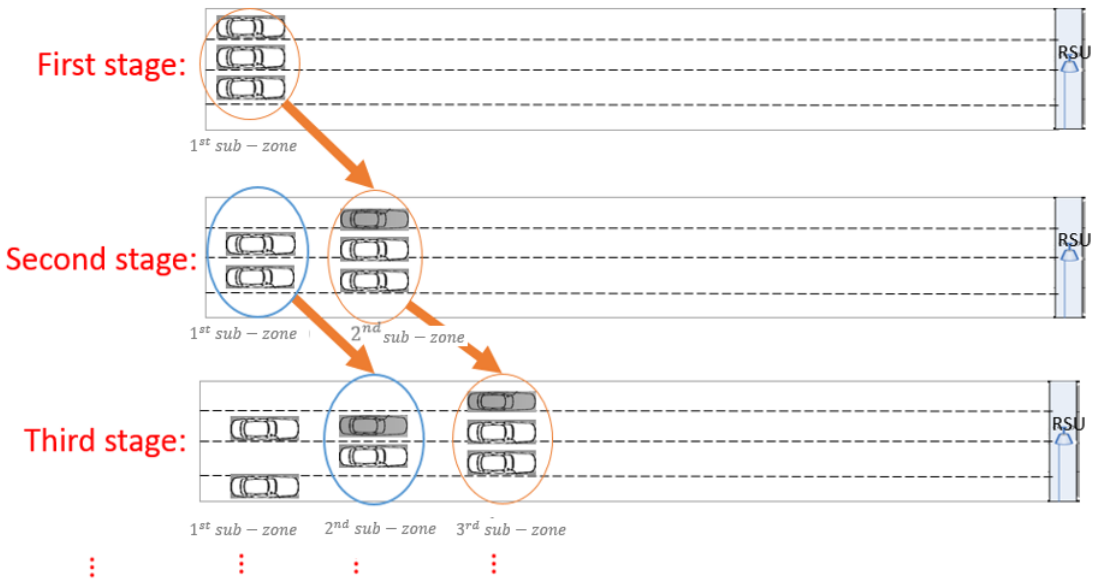


Figure 3-7. The step by step process of contention for vehicles

The analysis process of successful reservation ratio will be described as follows. At the first stage, there are α vehicles flow in the reservation zone, that is, $N(1) = n(1,1) = \alpha$. After the first contention for the α vehicles, the stage comes to the second one, we have to calculate the number of vehicles without getting the channel access, since the collision probability for a vehicle is $p_c(N(1), cw(1))$, we get $\mathrm{n}(2,2) = \mathrm{n}(1,1) \times p_c(N(1), cw(1))$. At the same time, there are still newly vehicles flow in the reservation zone, the expected value is $\mathrm{n}(2,1) = T_c(1) \times \lambda \times N_l$, where $T_c(1)$ is the duration for the contention of second group. Notice that $N(2)$ will be the summation of contending vehicles of first and second group, that is, $N(2) = n(2,1) + n(2,2)$. At the third stage, the remaining $n(2,2)$ vehicles will again contend the channel, we can use the similar way to derive $n(3,3) = n(2,2) \times p_c(N(2), cw(2))$. The vehicle of the second stage and first group will contend the channel, we can use the similar way to derive $n(3,2) = n(2,1) \times p_c(N(2), cw(2))$. At the same time, there are still newly vehicles flow in the reservation zone, the expected value is $\mathrm{n}(3,1) = T_c(2) \times \lambda \times N_l$. Notice that $N(3)$ will be the summation of contending vehicles from first to third group, that is, $N(3) = n(3,1) + n(3,2) + n(3,3)$. The explicit flow chart shows in the figure 3-8.

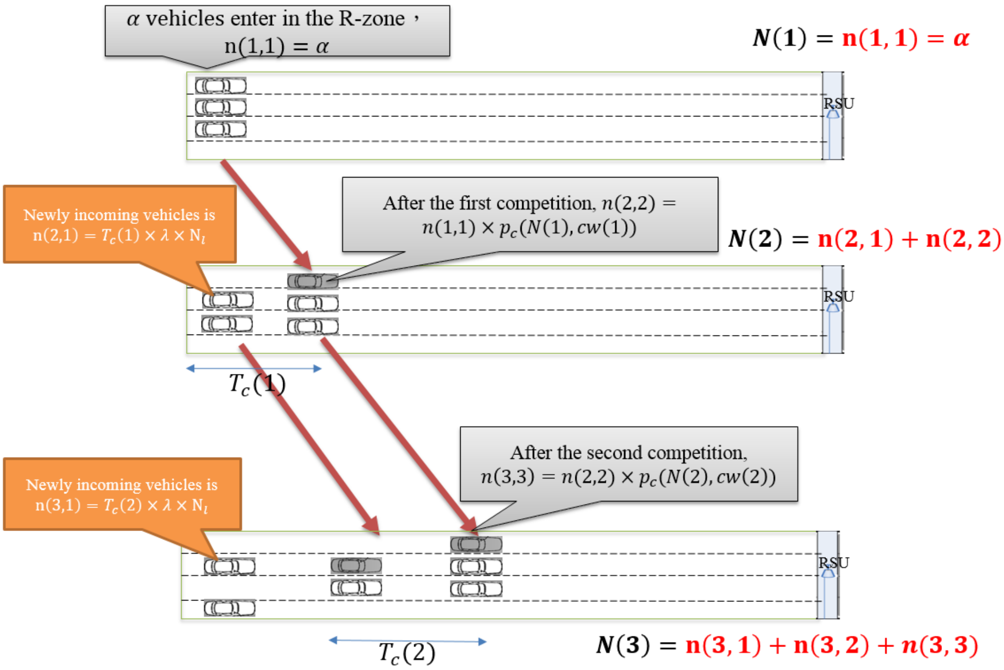


Figure 3-8. The explicit flow chart of step-by-step contention of vehicles

In general, the conducted equations are shown as follows:

$$n(i,j) = \begin{cases} n(i-1,j-1) \times p_c\big(N(i-1), cw(i-1)\big)\ for\ j > 1 \\ T_c(i-1) \times \lambda \times N_l\ for\ i > 1\ and\ j = 1 \\ \alpha\ \ for\ i = 1\ and\ j = 1 \end{cases} \tag{18}$$

and

$$N(\mathrm{i}) = \mathrm{n(i,1)} + \mathrm{n}(i,2) + \cdots + n(i,i) = \sum_{k=1}^{i} n(i,k) \tag{19}$$

Finally, the system will approach to a steady state after a time interval β, which means that the real number of contending vehicles will reach a constant value. We assume that it reaches the steady state when safisfying the condition: $N(\beta) - N(\beta-1) < 10^{-3}$, hence we get the number of vehicles in competition is $N(\beta)$.

In conclusion, since we derive the failure probability $p\big(N(\beta)\big)$

$$p\big(N(\beta)\big) = \{p|s(p, N(\beta), ssrl, m, cw) = 0, 0 < p < 1 \text{ and } p \in R\} \tag{20}$$

Here, the frozen probability is:

$$p_{fr} = p\big(N(\beta)\big) \tag{21}$$

And the successful channel reservation probability is:

$$g(i) = 1 - p\big(N(\beta)\big) \tag{22}$$

Chapter 4

The enviroment setup and evaluation results

4.1 Environment setup

Before discussing about the setup for the analysis and simulation, we have to derive the up-to-date real condition on the high-way, so that we can obtain more actual data corresponding to the current situation in Taiwan. According to the traffic flows that we have observed, there are two distinguishable periods of time, which are peak-hours and off-peak hours. In Taiwan, the peak-hours are often at 7-9 a.m. and 5-7 p.m. which are on-work time and off-work time, respectively; the rest of time are so called off-peak hours. In Jongli city of Taoyuan county where National Freeway No.1 passed through, and in NanKang district of Taipei City where National Freeway No.3 passed through, the traffic condition are almost similar that the average speed of vehicle is 100 km/hr with 0.5 vehicles per second of vehicle arrival rate for each lane in the off-peak hours, whereas the average speed of vehicle is 70 km/hr with 1.0 vehicles per second of vehicle arrival rate for each lane in the peak hours. The average speed of vehicle and arrival rate are summarized in Table 4-1.

Table 4-1. The real condition of high-way in Taiwan

Parameters	peak-hour	Off-peak hours
The average speed of vehicle	70km/hr	100km/hr
The vehicle arrival rate for each lane	0.8~1.2 veh/sec	0.4~0.6 veh/sec

We conduct the mathematical analysis using an analytical program written in C++. In our program, the parameters are declared as a form of macro, so that the developer can arbitrarily alter the value to see the variations of the successful reservation ratio.

With regard to the parameter setups, since the message transmitted between the RSU and OBU should have the highest priority, we consider the access category should be AC_VO. Also, the transmitting data rate is set to 3Mbps, which is the lowest regulated in the WAVE/DSRC spec, and the frame size is 1 Kb. More details are shown in the table 4-2.

Table 4-2. The parameter setup and the values for our analytical program

Analysis parameters	**Value**
Access category (AC)	AC_VO
The minimum of contention window size (CW_{min})	3
The maximum of contention window size (CW_{max})	7
Station short retry limit (*SSRL*)	7
Slot time (*aSlotTime*)	$9\mu s$
DCF Inter-frame space (*DIFS*)	$25\mu s$
Short Inter-frame space (*SIFS*)	$16\mu s$
Data rate (*R*)	3Mbps
Frame size (*D*)	1Kb
The length of reservation zone (l_R)	20m as default
Number of lanes(N_l)	4
Vehicle arrival rate(λ)	0.5 or 1.0 vehicle per second
Vehicle speed (*v*)	20m/s as default

Moreover, we conduct the simulation using Estinet 7.0 simulator [18]. The simulation scenario is in a 1000 meters four-lane high-way, with four T-RSUs using independent SCH for transaction procedure and one R-RSU using CCH for channel reservation. In addition, the average vehicle speed and vehicle arrival rate for each lane has different value in accordance with the simulated conditions. Transmission range and data transmission rate of each RSU and OBU are set as the minimum value defined in WAVE/DSRC spec, that is, 300m and 3Mbps, respectively. The detailed parameters are given in Table 4-3.

Table 4-3. The simulation parameter setups

Simulation parameters	**Value**
Length of highway	1 km
Lane width	3.5 m
Number of lanes	4
Number of T-RSUs	4
Length of R-zone	10, 20, 30m
Length of T-zone	8m
Average vehicle speed	70 or 100 kmph
Vehicle arrival rate	0.5 or 1.0 vehicle per second
R-Beacon interval	100 ms
Priority level of Reservation message	AC_VO
CFP of SCH	100%
Packet error rate	0%
Transmission data rate	3Mbps
Transmission range	300m

The following sections are organized as follows. In section 4.2, we will initially show the simulation results of proposed ETC system with varied length of R-zone and diffent vehicle arrival rate to observe the variation of the successful reservation probability, then we show the times of request message sent from vehicle with varied length of R-zone. Moreover, the default value of parameter is derived from table 4-1. In section 4.3, we will show the analytical results using our developed mathematical analysis within the parameter setup deriving from Table 4-2. Finally, in section 4.4, we compare the analytical results with simulation results, and we will find out both of these results are almost similar, which means that our mathematical analysis method has enough correctness.

4.2 Simulation results

Figure 4-1 illustrates the successful reservation ratio with varied R-zone length during the off-peak hours. We assume that the vehicle arrival rate is divided into three cases: 0.4, 0.5 and 0.6 (vehicle/sec). As what we have expected, the successful reservation probability with the case of vehicle arrival rate 0.6 is lower than others, this is because the number of vehicles in competition is higher than other cases so that the collision probability will be higher for each contention, which results in the reservation ratio lower. In addition, the reservation ratio will achieve 100% as the length of the R-zone reaches 6 meters, meaning that it is permitted for the R-zone length to be only set to 6m.

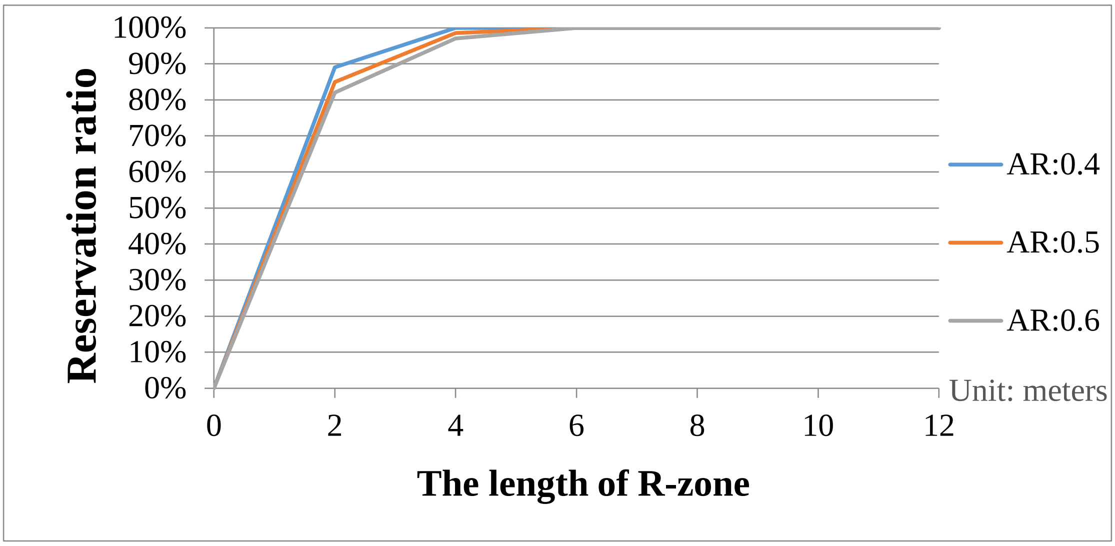


Figure 4-1. The reservation ratio with variable R-zone length in off-peak hours

In addition, Figure 4-2 illustrates the case of peak-hour with arrival rates 0.8, 1.0, and 1.2. From figure 4-2, we learn that the reservation ratio reaches 100% if length of R-zone is greater than 10m. Hence we can conclude that if the R-zone length is set to 10m, it will satisfy the traffic flow for both the off-peak hour and peak hour cases in Taiwan high-way scenario.

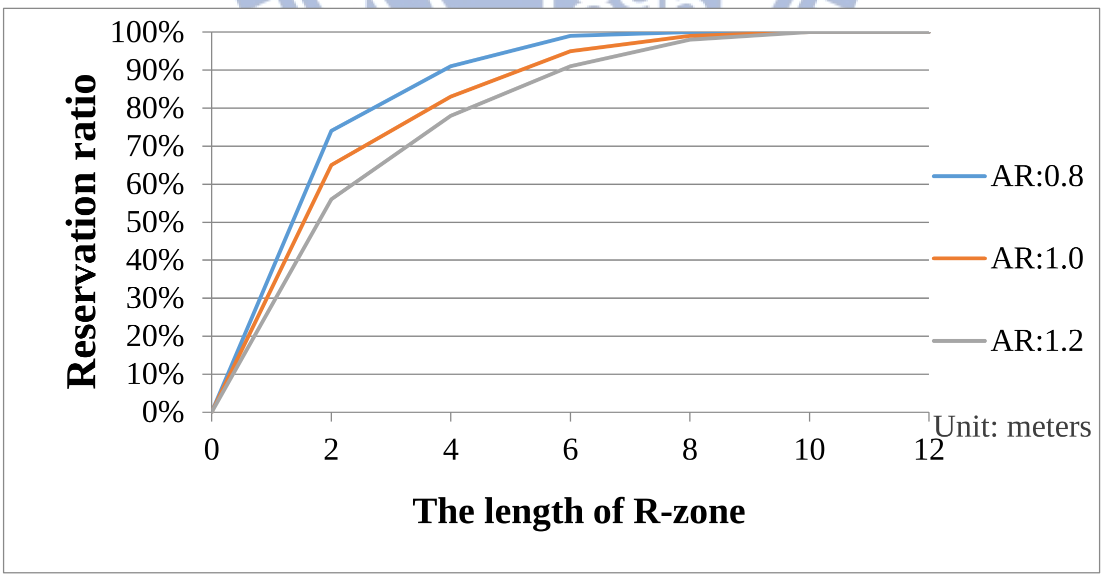


Figure 4-2. The reservation ratio with variable R-zone length in peak hours

Figure 4-3 illustrates the average times of request message sent by a vehicle within variable lengths of R-zone. From the figure, we will realize that the number of request times remains a constant for arrival rate 0.4 if the length of R-zone is greater than 4 meters. This is due to that the reservation ratio will reach 100% at that length, also meaning that the vehicle will not send request message as the displacement is over 4m, since the vehicle will absolutely get the channel reservation.

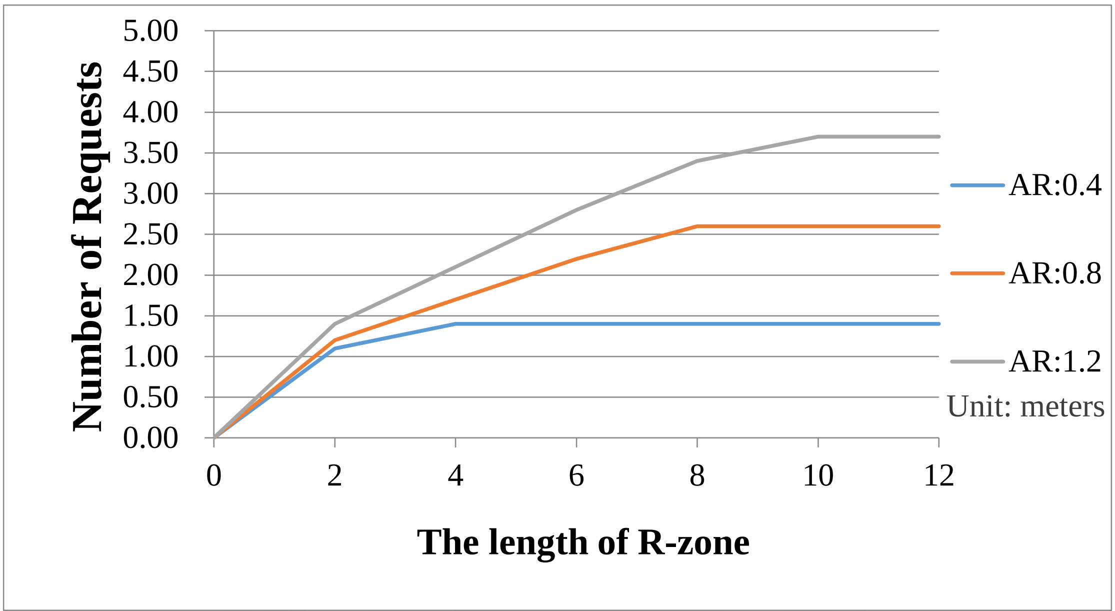


Figure 4-3. The avg. times of request sent by a vehicle within variable R-zone length

4.3 Analytical results

Figure 4-4 shows the successful reservation probability for a vehicle on the R-zone, with arrival rates: 0.3, 0.6, 0.9 and 1.2 (vehicle/second). The maximum length of R-zone is 20m, and the parameter on the x-axis is displacement of vehicles. From the figure, we observe that the reservation ratio is low when the vehicle arrival rate is high. Moreover, Figure 4-5 shows the case with variable data transmission rates, notice that the specification of WAVE/DSRC regulates transmission rate should be between 3Mbps to 27Mbps, hence if the data rate is too slow, the reservation condition will be deteriorated resulted from the high transmission delay. As we have seen from the figure, the reservation ratio sharply declines between the distances from 2 to 6 meters for the transmission rate 1Mbps.

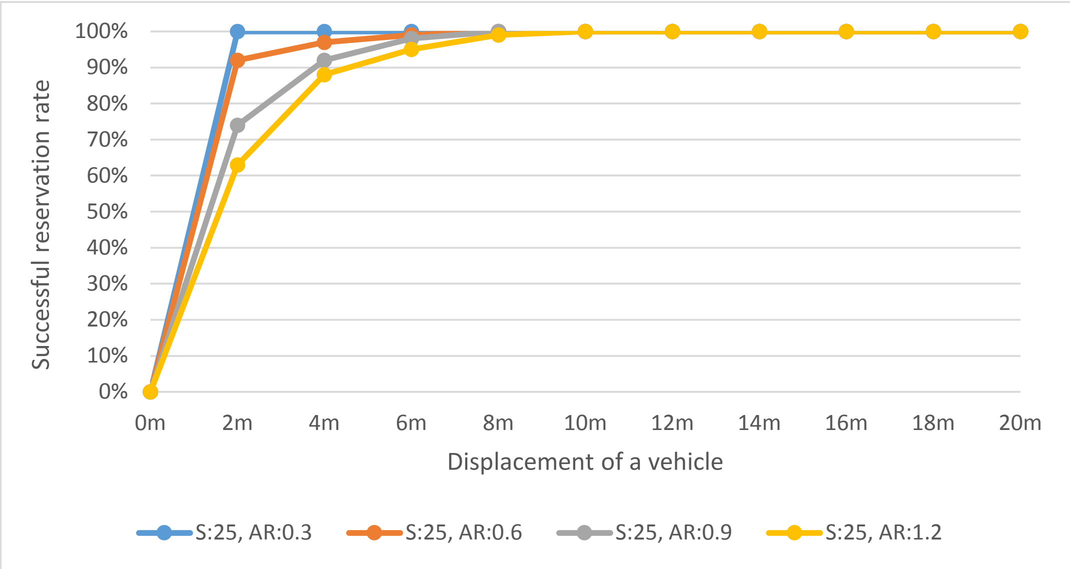


Figure 4-4 The length of R-zone is fixed 20m within variable vehicle arrival rate

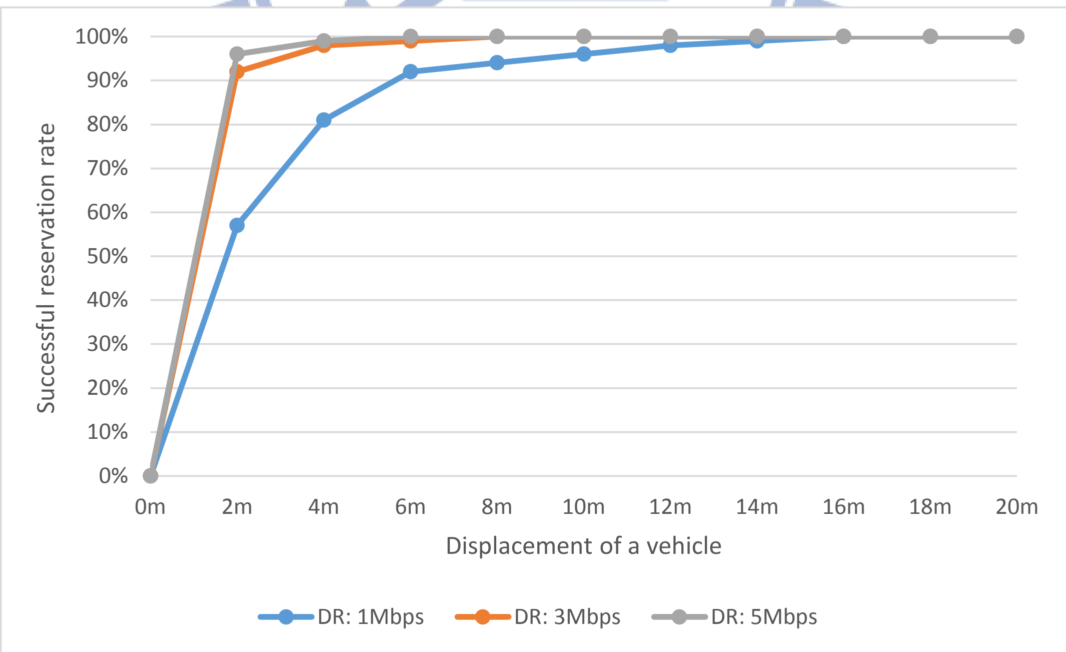


Figure 4-5 The length of R-zone is fixed 20m within variable data transmission rate

Figure 4-6 illustrates the case of short R-zone length, in which we adjust to 5 meters. Since a vehicle does not have too many opportunities for contending the channel access if the R-zone length is too short, as we see from the figure, the successful reservation probability for a vehicle does not reach 100% at the end of the R-zone. In our developed ETC system, the length of R-zone is suggested to set as 20m.

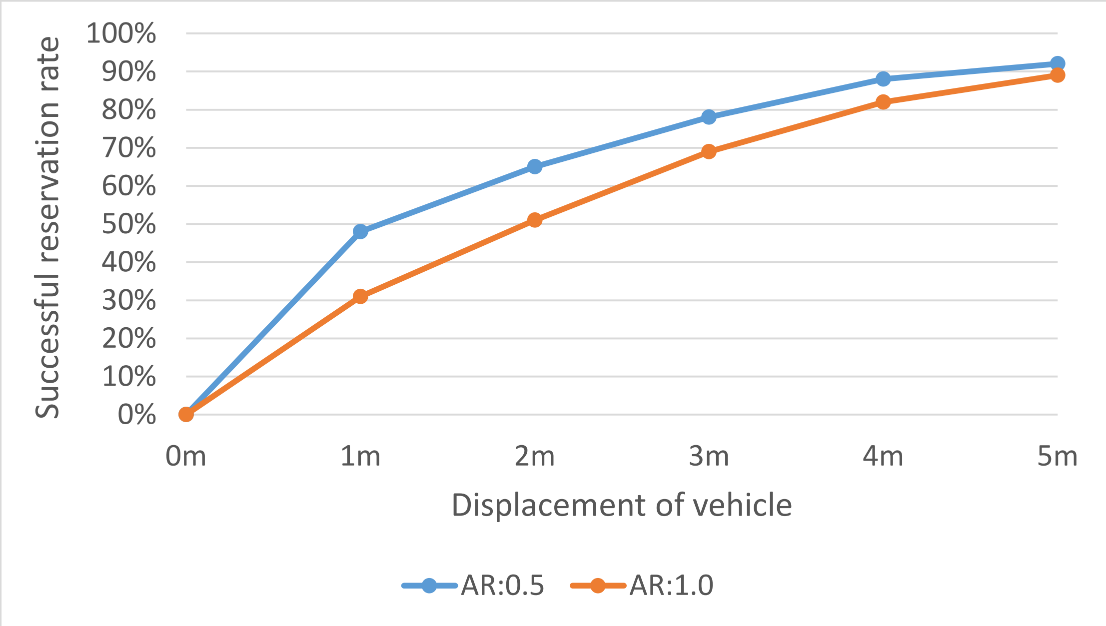
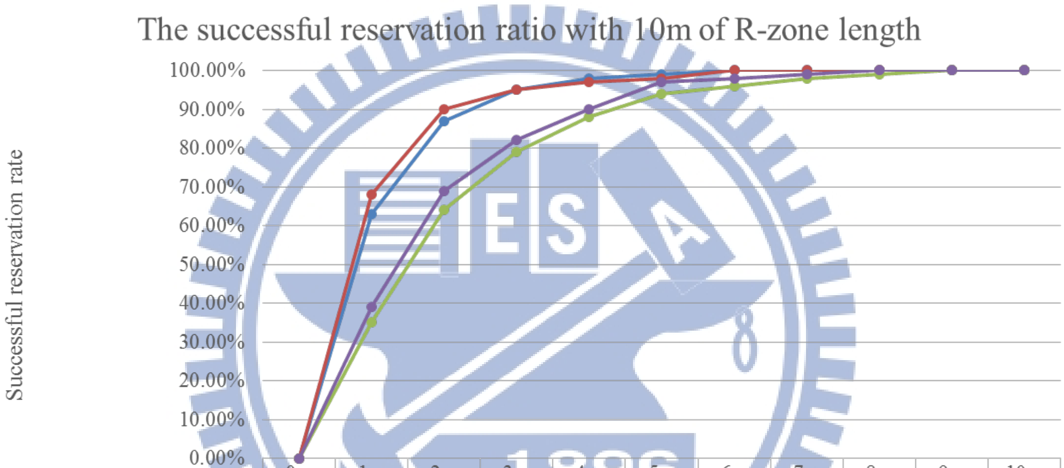


Figure 4-6 The length of R-zone is fixed 5m within different vehicle arrival rate

4.4 The comparison between simulation and analytical results

At the end, we will compare the simulated results with analytical results, observing the difference among them.

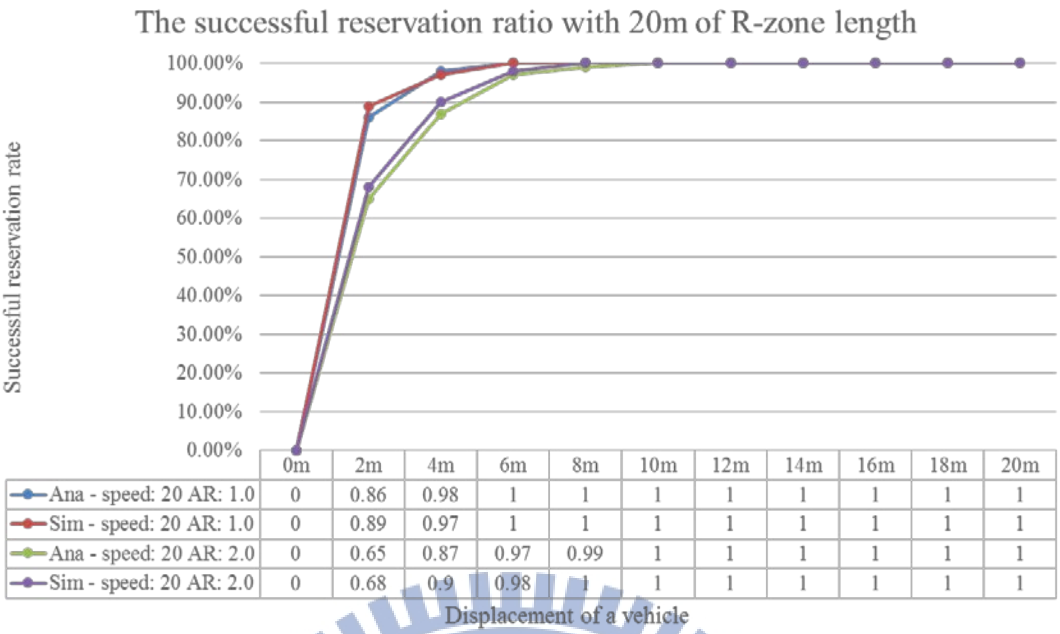
Figure 4-7 illustrates the reservation ratio for the fixed 10m R-zone length, the purple and red curves stand for simulated result and analytical results, respectively, both of them are under same condition within 20 meters per second as vehicle speed, 2.0 as arrival rate, and the data transmission rate is 3Mbps. Other parameter setup such as packet size and number of lanes of R-zone are following the value shown in Table 4-2. We see the ratio differentiation between these curves are at most 5% at 2m displacement, with slight gaps at other displacements. The other 2 curves in the graph has similar conclusion. Figure 4-8 expands the length to 20m, as we see, the reservation ratio is almost the same depicted in Figure 4-7 before displacement of 10m, which represents that even the length of R-zone expands to 30m or longer, the reservation ratio must be 100% at the end of the zone.



	0m	1m	2m	3m	4m	5m	6m	7m	8m	9m	10m
Ana - speed: 20 AR: 1.0	0	0.63	0.87	0.95	0.98	0.99	1	1	1	1	1
Sim - speed: 20 AR: 1.0	0	0.68	0.9	0.95	0.97	0.98	1	1	1	1	1
Ana - speed: 20 AR: 2.0	0	0.35	0.64	0.79	0.88	0.94	0.96	0.98	0.99	1	1
Sim - speed: 20 AR: 2.0	0	0.39	0.69	0.82	0.9	0.97	0.98	0.99	1	1	1

Displacement of a vehicle

Figure 4-7 The comparison between analysis and simulation for 10m R-zone



	0m	2m	4m	6m	8m	10m	12m	14m	16m	18m	20m
Ana - speed: 20 AR: 1.0	0	0.86	0.98	1	1	1	1	1	1	1	1
Sim - speed: 20 AR: 1.0	0	0.89	0.97	1	1	1	1	1	1	1	1
Ana - speed: 20 AR: 2.0	0	0.65	0.87	0.97	0.99	1	1	1	1	1	1
Sim - speed: 20 AR: 2.0	0	0.68	0.9	0.98	1	1	1	1	1	1	1

Figure 4-8 The comparison between analysis and simulation for 20m R-zone

Chapter 5
Conclusion

In this thesis, we propose an explicit mathematical analysis for our developed contention-free based ETC system. In our mathematical model, we use a step-by-step approach to compute the reservation ratio with variable displacement for a vehicle. Notice that the difference of our proposed mathematical model compared with others is that the contending nodes in our model is not always fixed n. Once a node gets the channel reservation, it will not contend for channel access again. In this thesis, we have shown a conductive method for computing the actual number of vehicles in contention within the reservation zone.

Finally, the evaluation results show that our analytical results almost match with the simulated results generated by Estinet 7.0 simulator, which means that our analytical model possesses enough accuracy for a set of parameters.

References

[1] S. Tsugawa, “The current trends and issues on ITS in Japan: Safety, energy and environment”, *Intelligent Radio for Future Personal Terminals (IMWS-IRFPT)*, pp. 1-2, Aug. 2011

[2] FarEasTone Telecommunication Co., Ltd., [Online]. Available: http://www.fetc.net.tw/.

[3] G-H Hsu; R-H Jan; C. Chen, “A novel non-payment vehicle searching method for multilane-free-flow electronic-toll-collection systems”, *Advanced Communication Technology (ICACT)*, pp. 904-909, 2012

[4] Y.L. Morgan, “Notes on DSRC & WAVE Standards Suite: Its Architecture, Design, and Characteristics”, *IEEE Communications Surveys & Tutorials*, Vol. 12, No. 4, pp. 504-518, 2010

[5] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)--Multi-channel Operation*, IEEE Std 1609.4-2010, Feb. 2011

[6] S. Eichler, ”Performance Evaluation of the IEEE 802.11p WAVE Communication Standard”, *IEEE Vehicular Technology Conference*, pp. 2199-2203, Fall 2007

[7] J. Alcaraz; J. Vales-Alonso; J. Garcia-Haro, “Control-based scheduling with QoS support for vehicle to infrastructure communications”, *IEEE Wireless Communications*, Vol. 16, No. 6, pp. 32-39, Dec. 2009

[8] Y-W Lan; J-H Yeh; J-C Chen ; Z-T Chou., “Performance enhancement of IEEE 802.11e EDCA by contention adaption” *IEEE Vehicular Technology Conference*, pp. 2096-2100, Spring 2005

[9] M. Barradi; A.S. Hafid; J.R. Gallardo, “Establishing strict priorities in IEEE 802.11p WAVE vehicular networks”, *IEEE Global Telecommunications Conference*, pp 1-6, Dec. 2010

[10] M.I. Hassan; H.L. Vu; T. Sakurai; L.L.H. Andrew, “Effect of Retransmissions on the Performance of the IEEE 802.11 MAC Protocol for DSRC” *IEEE Vehicular Technology*, pp 22-34, Jan 2012

[11] J.W.Tantra; C-H Foh ; A.B. Mnaouer, “Throughput and delay analysis of the IEEE 802.11e EDCA saturation” *IEEE International Conference on Communications*, pp 3450-3454 Vol. 5,16-20 May 2005

[12] Z-H Xiao; Z-Q Guan; Z-H Zheng, “The Research and Development of the Highway’s Electronic Toll Collection System”, *Knowledge Discovery and Data*

Mining (WKDD), pp. 359-362, Jan 2008

[13] A.S. Mustafa; M. Pitslava-Latinopoulou; G.A. Giannopoulos, "The multilane electronic toll collection system in Thessaloniki: Evaluation of its first 6 months of operation", *Vehicle Navigation and Information Systems Conference*, pp. 699-703, Sep 1994

[14] W-Y Shieh ; T-H Wang ; Y-H Chou ; C-C Huang, "Design of the Radiation Pattern of Infrared Short-Range Communication Systems for Electronic-Toll-Collection Applications", *IEEE Intelligent Transportation Systems*, pp 548-558, Sep 2008

[15] W-Y Shieh ; W-H Lee ; S-L Tung ; C-D Ho, "A novel architecture for multilane-free-flow electronic-toll-collection systems in the millimeter-wave range", *IEEE Intelligent Transportation Systems*, pp 294-301, Sep 2005

[16] J.D. Turner; R.M. Day, "Tolling applications using infra-red technology and the highest priority requirement: the enforcement system", *Electronic Techniques for Road Pricing and Tolling, IEE Colloquium on*, pp. 1-6, Mar 1995

[17] R-H Jan, "A WAVE/DSRC-based Highway Electronic Toll Collection System", *NSC project report*, No. NSC 100－2221－E－009－71－MY2, Oct 2013

[18] Estinet Technology, [Online]. Available: http://www.estinet.com/.