Performance Study of IEEE 802.11p for Vehicle to Vehicle Communications Using OPNET

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Abstract

IEEE 802.11p is the recently finalised protocol located at the bottom of the Dedicated Short Range Communication (DSRC) protocol suite, which supports Intelligent Transportation System (ITS) applications for both road safety and added value communication purposes. It has evolved from widely applied Wireless Local Area Network (WLAN) standards and it cooperates with peculiar higher layer protocols in order to carry out inter-vehicle communication. In this thesis, we focus on the performance study of road safety communication as being the vital application in ITS, which is very necessary not only because IEEE 802.11p is a relatively new protocol but also because it heavily relies on broadcast mode, thus distinguishing itself from other 802.11 counterparts. With the aid of OPNET, a powerful commercial simulator, different scenarios have been deployed in which one or more variable factors are involved, such as vehicle number, data packet size, communication distance, vehicle fleet topology, etc., in order to find out their impacts on DSCR and characteristics of 802.11p.

After analysing results data collected from hundreds of simulations, we found out that 802.11p represented a desirable performance in terms of latency and priority-oriented services throughout our simulation scenarios. However, packet collision caused by either media contention or hidden nodes turned out to be a relatively serious issue of vehicle communication and 802.11p seems in shortage of an effective mechanism to deal with it. What we can only hope is that under practical application, the media should always be lightly occupied and that there are few ACs with high priorities trying to contend resources simultaneously at any given time. Meanwhile, our analyses indicate that current 802.11p protocol might still need further modifications in order to address its inherent issues and enhance the communication performance.

Acknowledgements

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GLOSSARY

3G	**Third Generation**
AC	**Access Category**
ACK	**Acknowledgement**
ADSL	**Asymmetric Digital Subscriber Line**
AGC	**Automatic Gain Control**
AIFS	**Arbitrary Inter-frame Space**
AIFSN	**Arbitration Inter-Frame Space Number**
AP	**Access Point**
ASTM	**American Society for Testing and Materials**
BCH	**Basic Channel**
BEB	**Binary Exponential Backoff**
BER	**Bit Error Rate**
BS	**Base Station**
BSS	**Basic Service Set**
BTS	**Base Transreceiver Station**
CCA	**Clear Channel Assessment**
CCH	**Control Channel**
CDMA	**Code Division Multiple Access**
CRC	**Cyclic Redundancy Code**
CSMA/CA	**Carrier Sense Multiple Access with Collision Avoidance**
CTS	**Clear to Send**
CW	**Contention Window**
DCF	**Distributed Coordination Function**
D-MAC	**Directional MAC**
DSRC	**Dedicated Short Range Communications**
EDCA	**Enhanced Distributed Channel Access**
EDCAF	**Enhanced Distributed Channel Access Function**
EDCF	**Enhanced DCF**

EIFS	**Extended Inter-frame Space**
EIRP	**Equivalent Isotropically Radiated Power**
ERP	**Extended Rate PHY**
ESOP	**End of Service Period**
FCC	**Federal Communications Commission**
FEC	**Forward Error Correction**
FI	**Frame Information**
GI	**Guard Interval**
GPS	**Global Positioning System**
GSM	**Global System for Mobile Communications**
HCCA	**HCF Controlled Channel Access**
HCF	**Hybrid Coordination Function**
HR/DSSS	**High-Rate Direct Sequence**
IANA	**Internet Assigned Numbers Authority**
IBSS	**Independent BSS**
ICI	**Inter Carrier Interference**
IFFT	**Inverse Fast Fourier Transform**
IFS	**Interframe Spaces**
IR	**Intentional Radiator**
ISI	**Intern Symbol Interference**
ISM	**Industrial, Scientific and Medical**
ISTEA	**Intermodal Surface Transportation Efficiency Act**
ITS	**Intelligent Transport System**
ITU	**International Telecommunication Union**
LOS	**Line of Sight**
MAC	**Media Access Control**
MANET	**Mobile Ad-Hoc Network**
MIB	**Management Information Base**
MIMO	**Multiple-input and Multiple-output**
MPDU	**MAC Protocol Data Unit**

MS	**Mobile Station**
MSDU	**MAC Service Data Unit**
MTU	**Maximum Transmission Unit**
NAT	**Network Address Translation**
NHTSA	**National Traffic Safety Administration**
NLOS	**Non-LOS**
OBU	**Onboard Unit**
OFDM	**Orthogonal Frequency-Division Multiplexing**
OSI	**Open Systems Interconnection**
PCF	**Point Coordination Function**
PER	**Packet Error Rate**
PHY	**Physical Layer**
PLCP	**Physical Layer Convergence Procedure**
PMD	**Physical Medium Dependent**
PPDU	**PLCP Protocol Data Unit**
PSDU	**PLCP Service Data Unit**
PSID	**Provider Service ID**
PtMP	**Point to Multipoint**
PtP	**Point to Point**
QoS	**Quality of Service**
RIR	**Regional Internet Registries**
RR-ALOHA	**Reliable Reservation-ALOHA**
RSU	**Roadside Unit**
RTS	**Request to Send**
SAP	**Service Access Point**
SC	**Sub-Carrier**
SCH	**Service Channel**
SIFS	**Short Interframe Spaces**
SNR	**Signal to Noise Ratio**
STA	**Station**

TDMA	**Time Division Multiple Access**
TG	**Task Group**
TID	**Traffic Identifier**
TSID	**Traffic Stream Identifier**
TXOP	**Transmission Opportunity**
UNII	**Unlicensed national Information Infrastructure Band**
UP	**User Priority**
USDOT	**U.S. Department of Transportation**
V2I	**Vehicle to Infrastructure**
V2V	**Vehicle to Vehicle**
V2X	**V2V and V2I**
VANET	**Vehicular Ad-Hoc Network**
WAVE	**Wireless Access in Vehicular Environment**
WBSS	**WAVE Basic Service Set**
WG	**Working Group**
WIBSS	**WAVE IBSS**
Wimax	**Worldwide Interoperability for Microwave Access**
WLAN	**Wireless LAN**
WME	**WAVE Management Entity**
WRA	**WAVE Routing Advertisement**
WSA	**WAVE Service Advertisement**
WSM	**WAVE Short Message**
WSM	**WAVE Short Message**
WSMP	**WAVE Short Message Protocol**

Chapter 1 Introduction

1.1 Backgrounds

According to Traffic Safety Facts published by the United States National Traffic Safety Administration (NHTSA) in 2009, there were 5,505,000 vehicular crashes in that year, which resulted in a direct economic loss of $230.06 billion [1]. The numbers of fatalities, injuries and property damage were 30,797, 1,517,000 and 3,957,000, respectively [2]. Even though great effort has been made by car manufacturers to enhance the safety of severe crash accidents, the fatal number of crashes has not significantly declined in the last two decades; see Figure 1-1.

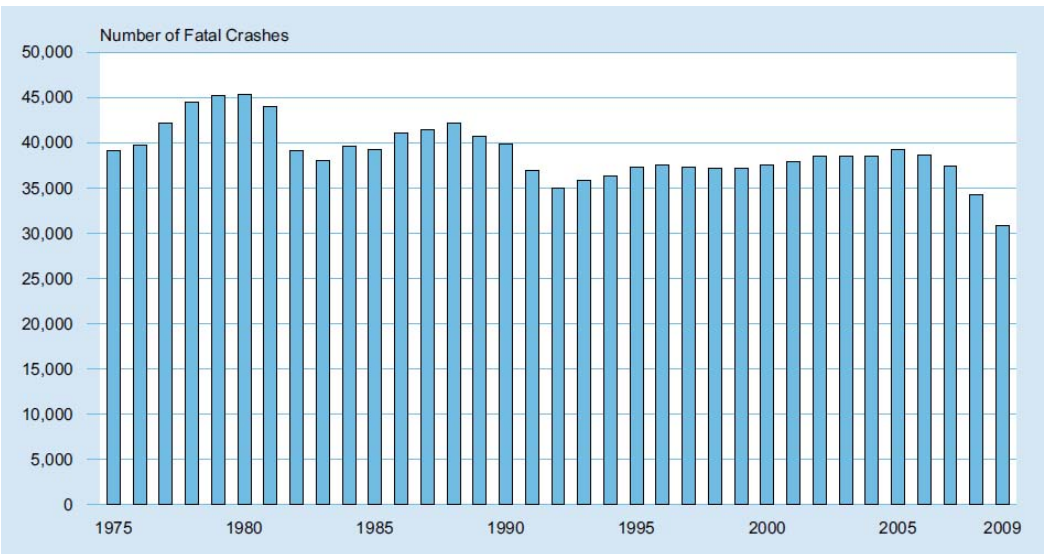

Figure 1-1 Number of Fatal Crashes from 1975-2009 [2]

For the sake of enhancing the efficiency, safety and convenience of transportation, the US Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 launched the national US (Intelligent Transport System) ITS programme, with US$660 million funding over six years. The core of ITS research conducted by the U.S. Department of Transportation (USDOT) has been clearly defined as connected vehicle research-“ – a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices. [1]". Among multi-year research, there are two aspects out of six in their main priorities, namely: Vehicle-to-Vehicle (V2V) Communications for Safety, and Vehicle-to-Infrastructure (V2I) Communications for Safety.

1.2 Justification for ITS in New Zealand

Even though ITS, V2V and V2I seem driven by the US industry, we should expect the deployment of ITS in New Zealand in the near future based on two facts; this is despite its population being only 1.3% of the United States' and its territory being only as big as the state of California.

Firstly, we compare the indicator from the World Bank: Passenger cars (per 1,000 people) [3] in 2008. Table 1-1 provides ranks of this indicator.

Table 1-1 Passenger cars per 1,000 people by country

Rank	Country name	2006	2007	2008
1	Monaco		748	732
2	Luxembourg			673
3	Iceland		667	661
4	**New Zealand**	**609**	**615**	**616**
5	Italy		591	596
	……			
21	United States		451	451

It is important to understand the feasibility of deploying ITS, which does not depend on how big the country is, since smaller coverage in most cases requires less investment on related devices. From the table above, we surprisingly find that New Zealand ranks in the top 4 and is the only country whose population is over one million. Meanwhile, every 1,000 Americans generally own 451 cars, yet it only ranks 21st, thus indicating around 32% lower than New Zealand. Given that the USA has invested billions of dollars on ITS, it is logical to assume that New Zealand, with a very close condition, could do it as well.

Secondly, it is necessary to compare traffic accidents between these two countries according to [2] and the New Zealand Crash Report 2009 [4], which is given in Table 1-2.

Table 1-2 Crash parameters between NZ and USA with derivative results

2009	New Zealand	United States
Population in Thousands	4315.8	307007
Number of Vehicles in Thousands	3220.3	257494*
Number of Injuries	14541	2217000
Number of Fatalities	384	33808
Number of Injury Crashes	10788	1517000
Number of Fatal Crashes	337	30797
Results		
Injured per Crash	1.347886541	1.461437047
Fatality per Crash	1.139465875	1.097769263
Injured per 1,000 vehicle	4.515417818	8.609909357
Fatality per 1,000 vehicle	0.119243549	0.131296263
Injury Crashes per 1,000 persons	2.49965244	4.941255411
Fatal Crashes per 1,000 persons	0.078085175	0.100313674
Crashes per 1,000 persons	2.577737615	5.041569085

*: There is no number of vehicles in 2009 provided by the NHTSA; thus, we used 2008 data instead.

By reviewing the table listed above, we can conclude that the number of crashes per 1,000 in New Zealand is around only half of the USA's, which does not mean that Kiwis must have better driving behaviour than Americans, since there are lots of factors involved in causing a car crash. Meanwhile, we should not distinguish between fatal accidents and accidents causing injury, as every crash is harmful to the public and the result in most cases is unpredictable. Furthermore, 14,925 causalities during just one year in a country with 4 million people is too high and there is no significant difference of Injured per Crash between two countries. The most significant statistic turns out to be the number of fatal crashes per 1,000 people being 30% lower than the United States; the Fatality per Crash is higher in New Zealand, thus indicating that more occupants, including drivers and passengers, lost their lives in accidents.

1.3 Vehicular Ad-Hoc Network (VANET)

A VANET is a form of mobile ad-hoc network, which provides communications to nearby vehicles with fixed equipment in order to improve road safety [5]. In fact, VANET is a very special case of Mobile Ad-Hoc Network (MANET) and shares lots of similarities with it. Concerning ITS, which is actually a very abstract term and a concept with many substantial research areas involved, the VANET is the most vital part of ITS research, thus proving the platforms of V2V and V2I communication as being two key components in ITS. The former is defined as a dynamic wireless exchange of data, at least including position, speed and location of vehicles, in order to sense threats and hazards, calculate risk, and issue driver advisories or warnings. On the other hand, V2I for safety focus on the exchange of critical safety and operational data between vehicles and highway infrastructure intended to primarily avoid or mitigate motor vehicle crashes, as well as enable a wide range of other safety, mobility, and environmental benefits [6]. Figure 1-2 provides an example of a V2V and V2I communication scenario.

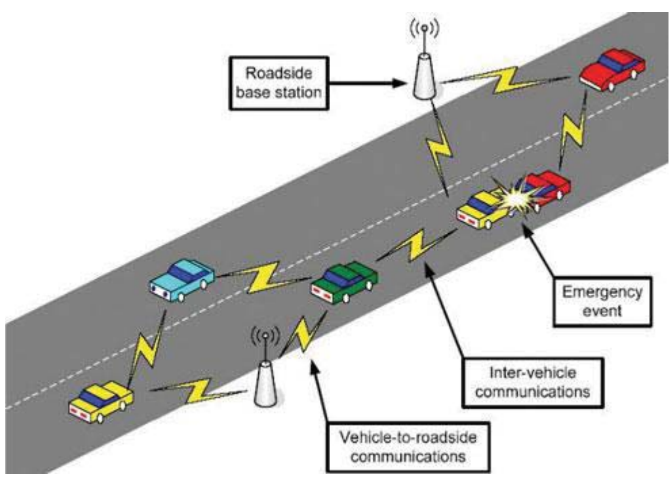

Figure 1-1 VANET Communication Scenario [7]

However, it may sound reasonably simple to let vehicles communicate with each other; the design and deployment of VANET actually face significant technical challenges, for example:

1. Unpredictable Wireless Communication Environment: VANET has to cope with unfavourable characteristics of wireless communication, such as multi-path propagation, fading and the Doppler effect.
2. Decentralised and self-organised Topology: The highly dynamic changes in VANET and the mobility of vehicles make it hard to synchronise and manage the transmission events, thus resulting in channel efficiency and frame collision.
3. Security and Privacy Issue: As we will see in the following chapters, many potential protocols for VANET are heavily based on broadcasts and are without a normal authentication mechanism for a time-critical application purpose. These attributes will inevitably bring about security issues, such as a broadcast storm.

1.4 Objectives and Outline of the Thesis

The main objective of the thesis is to present and evaluate the control channel (CCH) performance of VANET, based on IEEE 802.11p. As a recently finalised standard, current research of its performance is only at initial stage .Our literature review indicates that a comprehensive study of the standard that takes complex network topologies and high dynamic environment into consideration, is not available. As a result the work undertaken for this project was quite necessary, whereby we concentrate on its physical layer (PHY) technology and protocol of media access control (MAC) layer. Different simulations will be made in order to evaluate different characteristics of VANET for each access category (AC), such as delay, collision rate, reaction to changing vehicle numbers, and packet size, etc. We also provide an outline of this thesis through chapters, which are as follows:

Chapter 1 points out the necessity of ITS for the main purpose of enhancing road safety and it also introduces the concept of VANET, which provides a platform for V2V and V2I communication.

Chapter 2 depicts the development history of short range communications (DSRC), based on IEEE 802.11p and advantages in contrast with other VANET communication technologies.

Chapter 3 describes the PHY characteristics of IEEE 802.11p, including its radio link technology, spectrum, channel bandwidth, format of PHY data unit, transmission power and propagation modelling.

Chapter 4 introduces the MAC protocol for the 802.11 family and focuses on the mechanism of Enhanced Distributed Channel Access, which is adopted by IEEE 802.11p for the purpose of providing Quality of Service (QoS).

Chapter 5 examines the special topology of VANET under 802.11p, a mechanism of a multi-channel operation and a frame format of the WAVE Short Message (WSM) protocol, which is the very one that differs 802.11p from other WLAN standard counterparts.

Chapter 6 details simulation principles and element configuration of OPNET. Meanwhile, some fundamental phenomena, such as delay, distance and packet size impacts, will be analysed, thus acting as a basis and an indispensible one for Chapter 7.

Chapter 7 involves more complex simulation scenarios under multiple variables and dynamic changing network topology, in order to review the overall performance of VANET and further study the characteristics of each AC.

Chapter 8 provides conclusions of our study and recommends the enhancement of the software simulator as well as protocols for further study.

Chapter 2 Communication Technology for VANET

2.1 Overview

As mentioned previously, VANET is just a platform for vehicle communication, where different technologies are capable of being applied. Generally speaking, communication technologies can be divided into two categories in terms of topology, namely centralised and decentralised [8]. The mobile network, whether 2G or 3G, is the most typical example of a centralised technology. However, concerning requirements for safety-critical applications, such as latency and priority service, it turns out to be unsuitable to VANET. Thus, almost all efforts are made on the development of decentralised or Ad-Hoc communication technology for vehicle communication.

Meanwhile, the communication technology can be divided into two major parts: radio link technology and protocol, which are tightly dependent on each other. The former includes channel access method, modulation scheme, bandwidth, etc. A protocol is a set of rules for how information is exchanged over the network, which exists in every layer of a communication system, whereby Media Access Control (MAC) and Physical Layer (PHY) protocols are the most important ones.

2.2 Dedicated Short Range Communications (DSRC)

Dedicated Short Range Communications (DSRC) are defined as one-way or two-way short- to medium-range wireless communication channels, which are specifically designed for automotive use and are a corresponding set of protocols and standards involving everything from PHY to application layer for VANET [9]. The standardisation of DSRC began within the American Society for Testing and Materials (ASTM) subcommittee, E17.51, which takes charge of reviewing issues related to vehicle roadside communications [10]. In July 2003, it published the last standard version, E2213-03 (ASTM 2003), for DSRC, which is heavily based on the 802.11a standard by combining slightly changed PHY and MAC layers specified in IEEE 1999 and 2003, respectively.

After 2003, the task of developing DSRC standards has been put in the hands of two working groups (WG) of IEEE, namely P1609 WG and 802.11p WG. The former focus on standards from higher MAC layers to application layers and also developed a P 1690 protocol suite called Wireless Access in Vehicular Environment (WAVE) [11]. The latter concentrates on lower MAC and PHY. The drafts of 802.11p were developed based on ASTM 2003 between 2005 and 2009, according to the latest IEEE WLAN standard, and it was finally approved on July 15, 2010. Therefore, DSRC contains both WAVE and 802.11p. Figure 2-1 illustrates protocol architecture for DSRC.

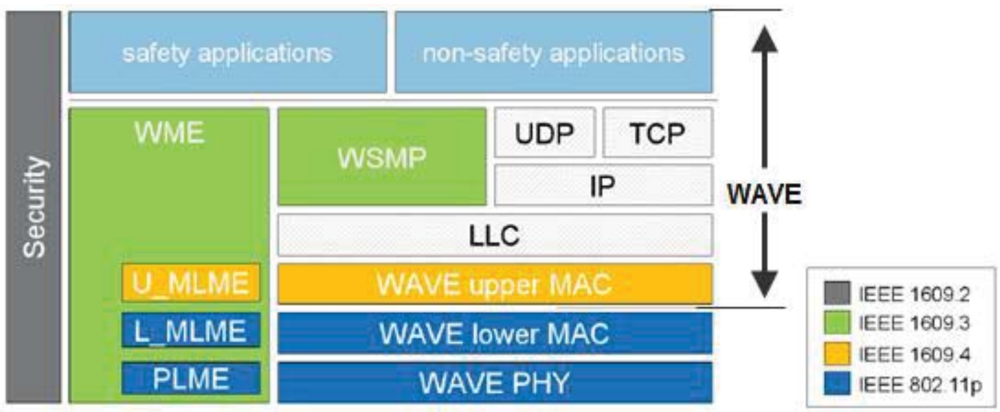

Figure 2-1 Protocol Architecture for DSRC [12]

In respect to the spectrum, a 75 MHz band from 5.850-5.925 GHz has been allocated by the Federal Communications Commission (FCC) in the United States. However, the EU made the decision for the DSRC spectrum much later than the USA, who allocated a 30 MHz band from 5.875-5.905 GHz on August 2008, thus sitting at the central of the USA band and now much narrower. It is apparently other countries that have their own decisions about what spectrum should be allocated to DSRC, whose statuses can be “in use”, “allocated” or ”potential”. Figure 2-2 illustrates the DSRC band allocations in different regions or entities.

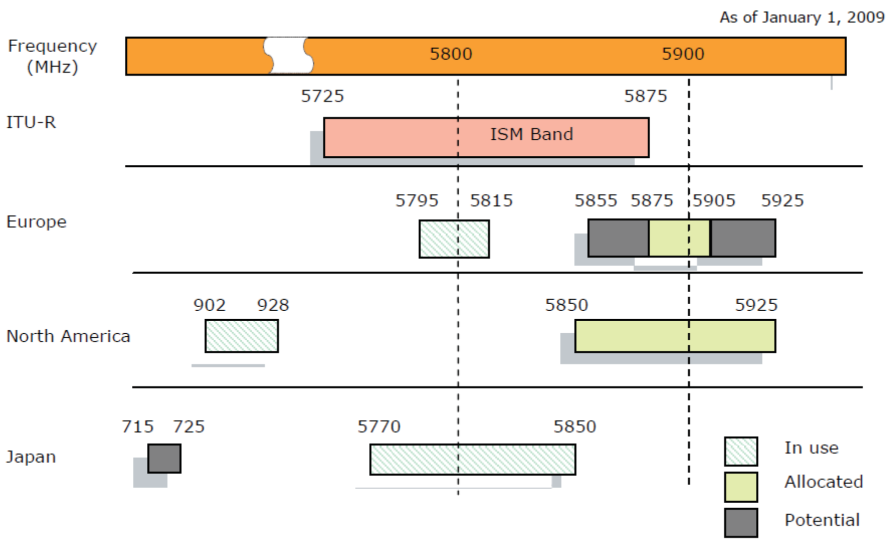

Figure 2-2 DSRC allocation in different regions or entities [13]

*The frequency band 5795-5815 MHz is designated for Road Transport and Traffic Telematics (RTTT) applications by CEPT/ECC Decision (02)01.

2.3 Other Communication Technologies for VANET

Nowadays, DSRC based on IEEE 802.11p is considered as the most promising one for VANET but it is definitely not the only choice. Throughout years of research, a considerable amount of technology has been proposed, whereby there are two draws of our attention; these will be introduced in the following:

The Reliable Reservation-ALOHA (RR-ALOHA) protocol is the key component of ADHOC MAC, a novel MAC architecture proposed by European Project CarTALK2000 [14]. Corresponding technology for a physical layer uses (Time Division Multiple Access) a TDMA mechanism in a distributed method. The media under RR-ALOHA is divided into fixed time frames and, like ALOHA, each node will occupy one time slot of a frame called Basic Channel (BCH) for sending its frame information (FI), which is a vector with M entries held by each member to indicate the sensing status in the previous frame. Each node is allowed to transmit only at its own BCH interval and listens for the remaining time slots, whose FIs will be marked as reserved or busy once successful transmissions have been detected, together with vehicle IDs. Thus, we can predict that if there is a new member joining in, it has to listen for an intact time frame before transmitting on a time slot considered as unoccupied. Therefore, if the time slot is marked by its ID in the whole FIs of the next frame, it indicates that this BCH is reserved for it in a two-hop neighbourhood for the purpose of hidden node avoidance.

Meanwhile, a Directional Antenna-based MAC protocol is another kind of VANET. As its name implies, the vehicle can transmit data in a desired direction by dividing 360 degrees into N sectors with a 360/N angle span each, which might sound like a very bizarre technology but is one that substantially exists with advantages of fewer transmission collisions and higher channel reuse efficiency [15]. The Directional MAC (D-MAC) is the most typical one for this kind. The adoption of D-MAC requires each vehicle to know geographic positions of themselves and neighbours by using GPS. Meanwhile, the media access mechanism is similar to 802.11, through involving Request to Send (RTS), Clear to Send (CTS) and Acknowledgement (ACK), which are sent to one or all sectors of 360 degrees. Any vehicles receiving such management messages are prohibited from transmitting until the initial node finishes its communication process. However, other vehicles outside the communication sectors will not be affected and will be able to conduct their own communication, namely simultaneous communication on the same frequency band used in different sectors.

However, it is necessary to point out some disadvantages of the above-mentioned two protocols. Concerning RR-ALOHA, it is based on the TDMA mechanism, which is difficult to meet relevant requirements of time-critical services provided by VANET, for example:

1. The number of time slots (N) is based on vehicle numbers in VANET and changes rapidly. Thus, it is hard to choose the value of N since too big a value will heavily shorten the transmission period for each vehicle and will waste bandwidth in cases with fewer vehicles in the network. Meanwhile, small N will cause BCH allocation failure, which often refers to Allocation Failure in (Global System for Mobile Communications) the GSM term.
2. The allocation of the time slot is mandatory regardless of vehicles going to send or not. Furthermore, at the same time, the topology swiftly changes, which generates a

lot of overheads - consequently in the data communication procedure. Also, each vehicle has to wait its turn for transmitting and a new joining member is unable to transmit at least one frame period, which are all fatal flaws for safety-oriented and delay-sensitive communication.

3. Synchronisation is essential for RR-ALOHA in order to coordinate the communication between vehicles, by letting them transmit between a very precious time span. Unlike the GSM network, where the base transreceiver station (BTS) will synchronise all mobile stations in a centralised manner, it is difficult and will bring about security issues for Ad-Hoc networks carrying out this task, whereby Time Advancement and multipath fading may cause chaos in communication.

In respect to protocol D-MAC:

1. First of all, it is very difficult to deal with the edge effect in wireless communication, which is supposed to happen in different sections, as the transmission energy will leak more or less to adjacent sections. Moreover, there is no definition of how many sections should be chosen for D-MAC. A vehicle might be located between two sections indicating that many vehicles will be unnecessarily informed and blocked from transmission.
2. This technology appears costly, and is therefore requesting many advanced antennae in order to fulfil this task.
3. Vehicles need to keep collecting geographical position information of all nearby counterparts and then decide which direction to transmit under a highly dynamic topology. For safety purposes, the Global Positioning System (GPS) coordinates will need to be sent in a broadcast manner, therefore wasting much more bandwidth. This is also very complex in terms of computation.

2.4 Necessity of 802.11p Performance Study

IEEE 802.11p has many advantages on other technology counterparts, due to three main reasons, as follows:

1. It is the groundwork for DSRC focused by USDOT.

2. The devices required by DSRC, which are based on 802.11p, are less costly than either RR-ALOHA or D-MAC. Meanwhile, it does not adopt the TDMA mechanism in order to provide more flexibility.
3. 802.11p applies the latest technologies on both PHY and MAC, such as Orthogonal Frequency-Division Multiplexing (OFDM) and Enhanced Distributed Channel Access (EDCA) in order to cope with rapidly changing communication environments and to provide priority-oriented services.

On the other hand, it is very necessary to further study the performance of VANET under 802.11p standards, mainly due to several reasons. First and foremost, it has just been finalised in the middle of 2011. Although for years in DSRC standard development, many research papers have been published, their standards that are inevitably being studied have some discrepancies with current 802.11p. For instance, in [16] and [17], Decentralized-TDMA and third generation (3G) cellular networks for mobile communication were studied for VANET communication. Secondly, the simulations for the VANET performance study nowadays are primarily conducted by NS-3 or OMNET++, which are public-source discrete-event network simulators based on C++. However, they are generally lacking systematic and complete documentations and version control support [18]. Besides that, the study of VANET requires us to deploy relatively complex scenarios, including attributes of vehicles (velocity, trajectory and number), PHY (frequency, modulation mechanism and transmission power), MAC (EDCA, higher layers (Packet Generation Frequency, size and traffic type), etc., which are either not included or are guaranteed by these contributed open-source simulators. Thus, in this thesis, we adopt OPNET as a full-featured commercial simulator, which is specialised for network research and development in order to better study and analyse the performance in VANET.

2.5 Summary

In this chapter, we introduced DSRC as the most promising communication technology for VANET. Recently finalised IEEE 802.11p is the basis of DSRC and is supposed to overcome many disadvantages of traditional vehicular communication technologies. It is very necessary to further study the performance of 802.11p, which will be conducted by commercial simulator, OPNET.

Chapter 3 Physical Layer Technology of 802.11p

3.1 Overview of Physical Layer

PHY is the lowest layer of the Open Systems Interconnection (OSI) model of a communication network ,whose functionality of PHY is transmitting raw bits through the network medium. Most of the time, the PHY layer of 802.11 or other wireless communication standards can be divided into two sub-layers, namely the Physical Layer Convergence Procedure (PLCP) sublayer and the Physical Medium Dependent (PMD) sublayer. The former works between the MAC layer and PMD layer, whereby it maps the bits into symbols and adds its own head to create PLCP Protocol Data Units (PPDUs). The PMD layer, on the other hand, is in charge of transmitting these symbols into the medium.

In respect to PHY design, two factors are generally taken into consideration. These are the medium type and end user expectation, which involve but are not limited to wired or wireless, working frequency, sending rate, throughput, modulation technology, etc [19]. Concerning wireless communication, which is more complex than its wired counterpart, it requires more effort on this layer, especially in elements, such as channel modeling and high reliability, in order to fulfill the proper operation of communication.

Current Wireless LAN (WLAN) technology largely depends on three PHY types defined by IEEE, namely OFDM PHY, High-Rate Direct Sequence (HR/DSSS) PHY, and Extended Rate PHY (ERP) adopted by 802.11a,p/b/g, respectively, which remarkably distinguish between each other by including multiplexing, modulation, and framing mechanisms.

3.2 Introduction of OFDM

Within the three PHYs mentioned above, OFDM PHY is the very one that draws our attention. It is the one which 802.11a/p and other latest technologies are dependent on, such as Asymmetric Digital Subscriber Line (ADSL) and Worldwide Interoperability for Microwave Access (Wimax). The OFDM-based transmission scheme can provide high rate transmission while maximising spectrum efficiency in tough channel environments, whereby a high bit stream is divided into several low bit streams and is transmitted by orthogonal overlapped sub-carriers (SCs). Figure 3-1 shows a block diagram of the OFDM system.

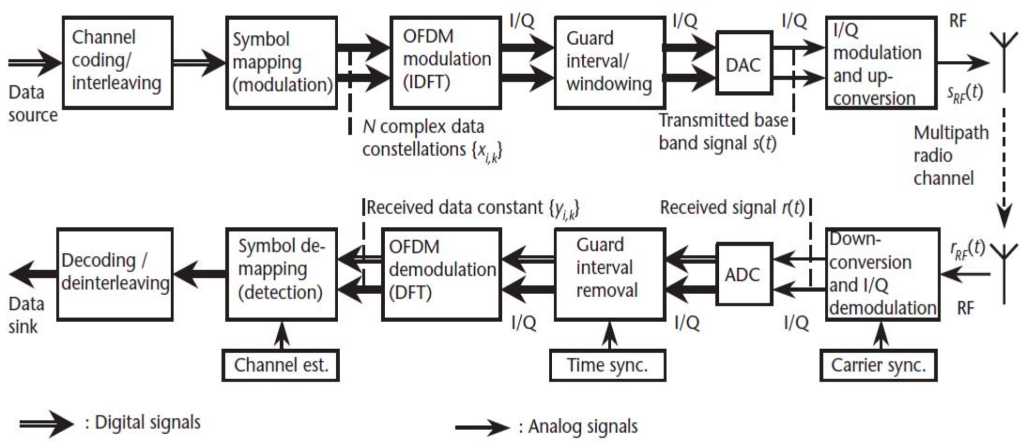

Figure 3-1 Block diagram of OFDM System [20]

Based on the figure given above, some attributes of the OFDM mechanism will be briefly introduced, as follows:

1. There are three kinds of forward error correction (FEC) options in OFDM wireless systems 1/2, 2/3 and 3/4.
2. There are four kinds of modulation mechanisms provided in 802.11 OFDM systems (BPSK, QPSK, 16 QAM and 64 QAM), which cooperate with different coding rates in order to provide appropriate bit rates called dynamic rate shifting.
3. A lower baud rate modulation should be used in tough environments and modulations, such as 16 or 64 QAM, which need more power in order to transmit and to be applied in a relatively ideal condition.
4. A cyclic prefix, which is a copy of the last portion of the data symbol appended to the front of the symbol during the guard interval, acting as a Guard Interval will be put on each OFDM symbol in order to overcome Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI). The former is often caused by time dispersive

environments in the form of multipath propagation. On the other hand, ICI may happen due to the Doppler effect or an asynchronisation between transmitter and receiver. Figure 3-2 provides illustrations of ICI and ISI.

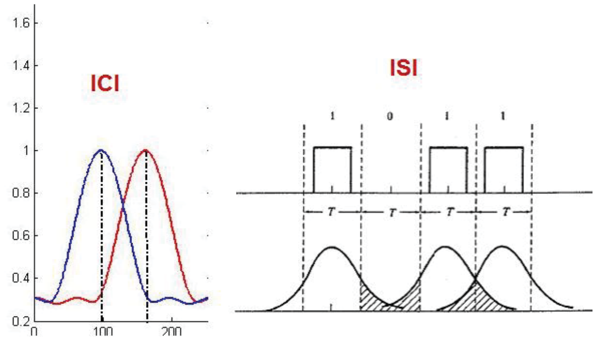

Figure 3-2 ICI and ISI

3.3 Comparison between 802.11a and 802.11p

As mentioned above, both 802.11a and p adopt OFDM technology. Since 802.11p is an amended version of the 802.11a standard, only minor changes have been made. Table 3-1 gives a comparison between these two standards [21].

Table 3-1 Comparison between 802.11a and 802.11p

Parameters	IEEE 802.11a	IEEE 802.11p	Changes
Bit rate(Mbit/s)	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	Half
Modulation mode	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM	No Change
Code rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	No Change
Number of active subcarriers	52	52	No Change
Symbol duration	4 µs	8 µs	Double
Guard time	0.8 µs	1.6 µs	Double
FFT period	3.2 µs	6.4 µs	Double
Preamble duration	16 µs	32 µs	Double
Subcarrier spacing	0.3125 MHz	0.15625 MHz	Half

We can see 802.11p differs itself from 802.11a on many PHY parameters, although all these changes are actually caused by merely halving the bandwidth of 802.11a to 10 MHz, since OFDM parameters, such as preamble duration, symbol duration, and bit rate, have a linear relationship with subcarrier spacing. The three most important parameters will be introduced, as follows:

1. Number of Subcarriers:

   We can see that the number of active subcarriers for both standards is the same (52). The reason to call it active is that the number of SCs defined by them is 64, whilst in a status of being either active or inactive [22]. Thus, it is not very accurate to say 802.11a or p has 52 or 48 subcarriers. However, for the purpose of avoiding neighbouring mask interference, the lower-end six SCs and upper-end five SCs are set as inactively reserved for the guard band, together with a central Direct Conversion band (DC-band). It causes the remaining number of SCs in active status to be 52. Since channel widths of 802.11a and p are 20 and 10 MHz, respectively, the spacing for each SC becomes 0.3125 MHz for 802.11a and half that value for 802.11p. Furthermore, 4 SCs out of 52 are pilot SCs that carry no information from an input data stream, except timing and frequency information for the purpose of synchronisation. Therefore, the total number of SCs used to carry "useful" information is only 48.

2. Subcarrier frequency spacing (Δf) and FFT period T_{FFT}

   Δf = channel bandwidth/total subcarrier number (including inactive ones). Thus, Δf for 802.11p will be 10 MHz/64=156.25 kHz, which is half the value of 802.11a. T_{FFT} defines the sampling duration of FFT for each subcarrier equal to $1/\Delta f$. Thus, T_{FFT} will be 3.2μs and 6.4μs for 802.11 a and p, respectively. The following attributes are all dependent on T_{FFT} but we need to know that the root is subcarrier spacing.

3. Data Rate

   The reason the code bit rate of 802.11p is only half of its 802.11a counterpart is due to doubling of the symbol duration to 8μs, which makes 6 MBd for 802.11p, rather than 12 MBd as in the 802.11a case. This characteristic further indicates that the data rate of 802.11p, whilst under the same modulation and coding rate as 802.11a, will only get half of its rate level. It is actually very reasonable for VANET, based on several facts. Firstly, standards, such as 802.11p, for vehicular communication are mainly for safety purposes involving lots of short message communications rather than continuous communication for home or office usage. Thus, the driver will experience no difference to the latency of receiving a message around several Kbs by lowering the capacity from 54 Mbps to 27 Mbps. On the other hand, the data rate provided by each standard of 802.11 is in a very ideal condition. Concerning VANET, a highly dynamic environment and a vehicle number within a communication zone effectively contribute to throughput much more than sending a data rate. Also, of major importance is that it is worthy to sacrifice some high data rates, namely 36, 48, and 54 Mbps in general for very good conditions, which are rarely able to be met in the V2V case, in order to provide a more robust transmission mechanism by doubling its symbol duration. Additionally, only 3, 6 and 12 Mbps are compulsory for applying 10 MHz OFDM PHY; the rest are optional [23].

3.4 OFDM PLCP

3.4.1 Functions of PLCP

As mentioned at the beginning of this chapter, PHY of 802.11 standards can be sub-divided into PLCP and PDM sub layers. PLCP communicates with MAC through a service access point (SAP) and its main function is further processing MAC protocol data units (MPDUs), whilst often referring to PLCP service data units (PSDU) in PHY for transmission preparation. To be specific, when the PLCP layer receives PSDU from MAC, it will add three additional parts to it (preamble, a PLCP header and trailer) in order to form a PLCP frame, which is the same ideal from the 7 layer OSI model, whereby a MAC packet moves down to PHY to become a frame. Then, PLCP will provide data rate and transmit power information to the PMD sublayer, which further carries out an OFDM modulation task, including an inverse fast fourier transform (IFFT), a cyclic prefix attachment, and DAC, etc. Meanwhile, although the frame structure at the PLCP layer would be different, according to transmission technology, it would generally perform the same three functions. The first is called a Carrier Sense function. PLCP will ask PMD to continually check the status of the medium. If there are desired signals detected, PLCP will try to synchronise with the receiver by reading its preamble. On the other hand, when transmitting, PLCP will provide medium status information called PHY-CCA (Clear Channel Assessment) to MAC, which makes a further decision on transmission based on it. Concerning the transmit function, PLCP will direct PMD to be in the transmitting mode after having a TXSTART.request primitive, together with PSDU ranging from 0-4095 bytes, from the MAC layer. Within 20 microseconds, the PMD should send a preamble to antennae at the lowest rate of corresponding standards [14]. For 802.11p, the data rate will be 3 Mbps (actual gross rate is 6 MBd) in BPSK modulation in order to provide the most robust mechanism. Then, PDM will switch to maybe a different rate defined in PSDU for the rest of the frame. After the transmission, PLCP will send a PHY-TXSTEND.confirm primitive to the MAC layer, while asking PMD to go back to receive the status. Figure 3-3 illustrates the mechanism.

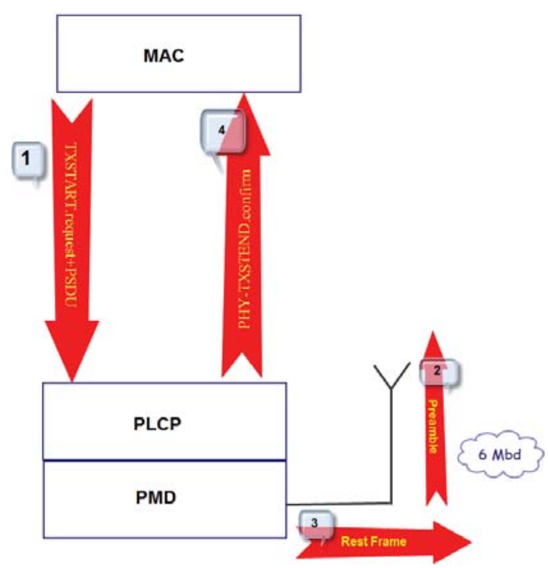

Figure 3-3 PLCP transmit function

Concerning the receive function, the situation becomes a bit more complex, as many more primitives will be involved. Firstly, if the PLCP learns from PMD that the channel is busy at the signal power level at at least -82 dBm [24], it will try to read the incoming frame preamble and synchronise with the receiver. Then, PLCP will send a PHY-RXSTART.indicate primitive as well as frame length & data rate information in the frame head to MAC, in order to let it know that there is a frame coming. Meanwhile, there is a bytes counter set in PLCP against the information received from the frame header helping it know when the receiving can be considered as completed, while also sending bytes of PSDU to MAC via PHY-DATA.indicate messages. After receiving the procedure, PLCP will further send a PHY-RXEND.indicate primitive to MAC [25].

3.4.2 OFDM PPDU Format

The frame format of the OFDM PLCP Data Unit (PPDU), whether 802.11a or p, is the same but with a different length. OFDM PPDU can be divided into three main parts: Preamble, Signal and Data Fields, which are shown in Figure 3-4.

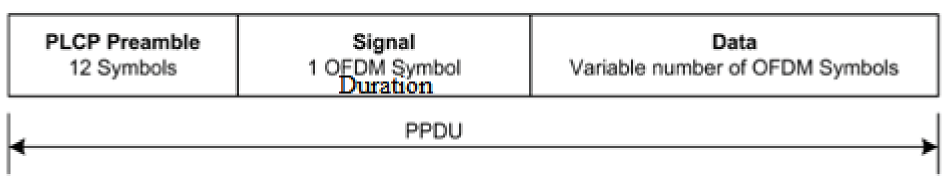

Figure 3-4 Format of OFDM PPDU

One thing needs to be noted here. Unlike TCP/UDP or an IP protocol, whose frame format can be defined exactly in bits, PPDU adopts both time duration and bits to express itself as some sub-parts, rather than being Data filed; these are variable in length but have a fixed duration.

The PLCP preamble field actually consists of three sub-parts: 10 short training sequences, a guard interval II (GI2), as well as 2 long training sequences. Figure 3-5 shows the detailed structure of the PLCP Preamble of 802.11p.

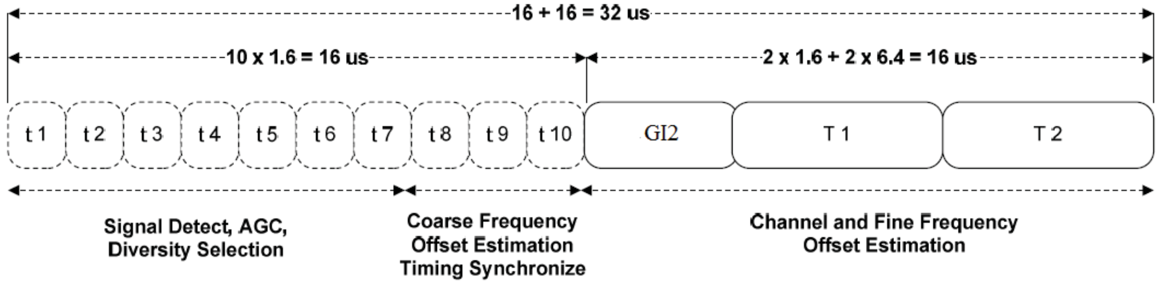

Figure 3-5 802.11p PLCP Preamble Structure

In respect to 802.11p, the duration of short training sequence T_S equals 1/4 of T_{FFT} at 0.8μs; therefore, the total duration of ten T_S is 8μs. The first 7 ones are used for signal detection, automatic gain control (AGC) and antenna diversity selection. The remaining three from t7 to t10 help to provide synchronisation as well as coarse frequency acquisition [26]. Since the PLCP preamble contributes a lot to successful transmission, it is worthy of putting a guard interval (GI2) between short and long sequences, which is 1/2 of T_{FFT}, twice the value of OFDM GI duration. Following two long training sequences, a doubled value of T_{FFT} is deployed for estimating channel impulse responses and a frequency offset. Thus, the total duration of the PLCP Preamble reaches 32μs for 802.11p. One thing needed to be noted is that the clear channel assessment (CCA) of PLCP is required to inform MAC that the medium is busy within the time after five short training sequences have been read.

The signal is a 24 bits long field. There is a misinterpretation by marking it "one OFDM symbol" in many places. As different modulations provide various baud rates, each OFDM symbol contains different bits. Even if we know that the Signal field is always sent in the most robust modulation mechanism, BPSK, when referring to 802.11a and p, to call Signal one OFDM symbol, is still not correct. According to what is mentioned above, there are 48 active subcarriers and one OFDM symbol representing 48 bits under BPSK. Thus, the Signal field is merely 1/2 of the OFDM symbol (under BPSK) in the PLCP frame. Considering a 1/2 coding rate at a PMD sublayer, it is more accurate to say that Signal field needs one OFDM symbol duration to be sent. Figure 3-6 gives a detailed structure of the Signal field.

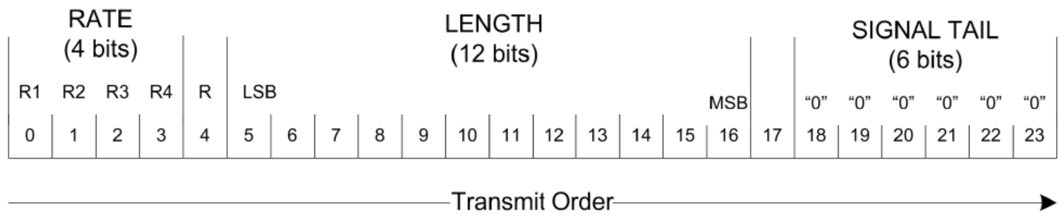

Figure 3-6 Structure of Signal Field

The first part contains 4 bits that are used to inform PMD which rates should apply to the Data field. For instance, 1101 means 6 Mbps, and 1001 indicates 16 QAM. Followed by 1 bit, the reserved subfield is always set to 0. The Length field represents how long PSDU is in bytes, which on the other hand indicates that any PSDU should not be over 4095 bytes as (2^12-1=4095). Actually, it is not practical to currently set PSDU that high for wired networks, as Ethernet frames only allow 1518 bytes at maximum [27], such as PPPoE and not to mention wireless networks, whose communication conditions are often worse than wired counterparts. Like the PLCP preamble, the importance of a Signal field is worthy of setting one parity bit for error detection of only the first 17 bits out of 24. Finally, the 4 bits at the Tail field are reserved and are all set to 0.

The Data field is composed of 4 sub fields. The first one is called Service field with 16 bits all set to be 0s, whereby the lower 7 bits are used for synchronisation at the receiver side and the upper 9 bits also are reserved. PSDU is the heaviest part of the PLCP frame, and for WLAN, whose size is on average 1024 bytes, generally. In the following 6 bits at the Tail field, all 0s are applied for improving the error probability of the decoder by returning the "zero state". We know that the PLCP frame will be sent to PMD for constellation mapping. In order to keep the integrity, the size of the frame must be the integer number of the OFDM symbol based on different modulation mechanisms. Therefore, the last Pad field of at least six bits long is used for this purpose.

3.5 Spectrum Allocation for 802.11p

3.5.1 Industrial, Scientific, and Medical Bands

They are license-free and often refer to ISM bands [28], which are defined by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). In the United States, the FCC controls the use of the ISM bands but it may differ in other countries due to local regulations. The ISM bands can be sub-divided into three categories as follows:

1. 1902-928 MHz (26 MHz wide, Industrial)
2. 2.4000-2.4835 GHz (83.5 MHz wide, Scientific)
3. 5.725-5.875GHz (150 MHz wide Medical)

As we mentioned previously, 5.850-5.925 GHz has been allocated for DSRC by the FCC in the United States, which is slightly overlapping with the medical band. The reasons for choosing a 5 GHz band rather than its two lower frequency counterparts in ISM are based on two facts:

4. Concerning the 900 MHz industrial band, although it has a stronger penetration capability due to a relatively low frequency, the bandwidth seems too narrow to be applied to V2X (V2V and V2I) communication and is already partially occupied by the widely deployed GSM 900 Network.
5. In respect to the 2.4 GHz scientific band, as most 802.11 standards, such as 802.11b/g/n, operate on this frequency, the interference turns out to be severe and makes it infeasible to be adopted by DSRC. For example, Figure 3-7 shows 802.11b/g signal interference in the CBD area of Auckland at 8:00 PM Saturday, 11th June 2011. More than a hundred Wi-Fi signals had been detected by a 14 dBi gain directional antenna.

Figure 3-7 Wi-Fi signal test in Auckland CBD

3.5.2 Unlicensed National Information Infrastructure Bands

The Unlicensed National Information Infrastructure Bands (UNII) is where 802.11a is frequency located. Although DSRC does not operate on exact frequencies defined by these bands but are close, it is worthy of being reviewed and analysed. UNII can be categorised into three discrete bands with a 100 MHz width each, as follows:

1 UNII-1 Lower 5.15-5.25 GHz

2 UNII-2 Middle 5.25-5.35 GHz

3 UNII-3 Upper 5.725-5.825 GHz

The IEEE defines the UNII-1 for indoor usage only and the maximum transmit power of 40 mW, followed by UNII-2 for either indoor or outdoor use at a maximum of 200 mW, as well as UNII-3 for outdoor point-to-point at 800 mW. The 802.11a works on all these three bands with 12 sub channels spaced at 20 MHz each, in which 8 channels are located at UNII-1/2, and the remaining 4 sit at UNII-3. Figure 3-8 illustrates the channel allocation of 802.11a.

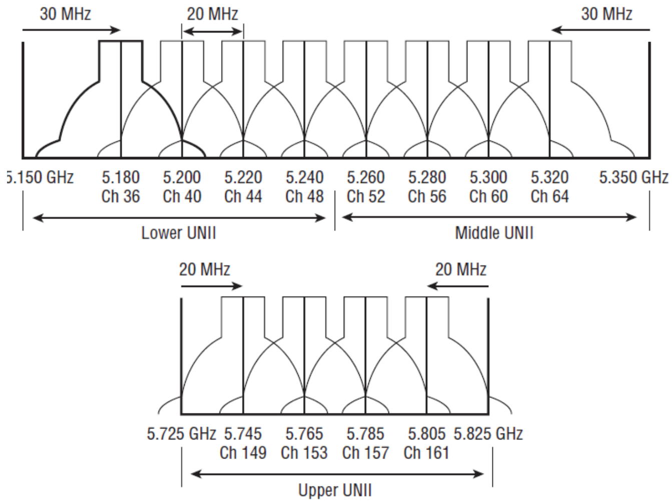

Figure 3-8 Frequency spacing of 802.11a

The channel at 5 GHz is much "cleaner" than its 2.4 GHz counterpart, due to the prevalence of 802.11b/g and the lesser adoption of 802.11a. Actually, a spectrum between 5-6 GHz is one of the most promising candidates for 802.11p standards. First, the Line of Sight (LOS) almost dominates the overall performance of wireless communication above 6 GHz. Below that, LOS and (non-LOS) NLOS both play important roles. Concerning V2I in vehicular communication, the roadside units (RSUs) can be densely deployed to mount tall enough but to only cover a relatively short range, such as 1 Km at a highway, where the clear sight environment often can be met. Secondly, the 2.4 GHz band is not only congested but is also not very helpful to vehicle communication as there is merely 7.66 dB extra loss through the use of 5.8 GHz, and the use of a free space loss calculation. Through comparing with the industrial band, if ISM can be simply overcome by using antenna gain technology, a 5.8 GHz signal would reach -77.66 dBm based on 30 dBm maximum transmit power, which is suitable for most sensitivity requirements. Thirdly, such a frequency can provide a higher data rate for time-critical communication, such as V2V.

3.5.3 DSRC Channel Arrangement

When we mention DSRC or 802.11p, the emphasis is on DSRC regulation in the US, due to the maturity and stability consideration. 802.11p works at a frequency band of 5.850-5.925

GHz, which overlaps with the Medical band of ISM. Considering a sideband phenomenon and the avoidance of interference to 802.11a, the lower 5 MHz out of the 75 MHz bandwidth is reserved as a guard band. The rest of the 70 MHz is sub-divided into seven 10 MHz channels. Figure 3-9 shows a chart of the channel arrangement.

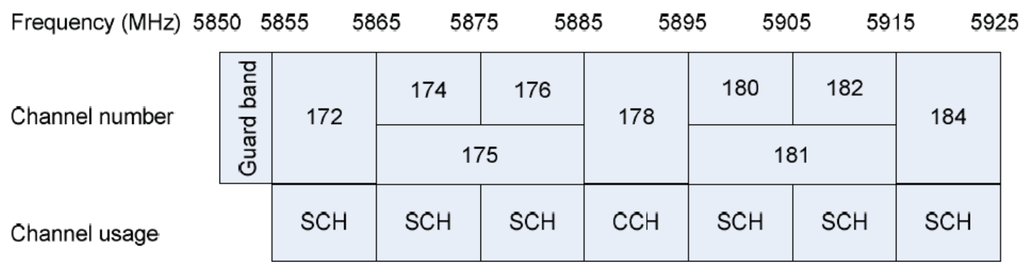

Figure 3-9 DSRC channel arrangement

As we can see, each channel is numbered with 10 MHz each. The way of calculating central frequency of each channel is borrowed from 802.11a, where f_c=5000 + 5*C_n in MHz, for instance, f_{176}=5000+5*176=5880 MHz. Meanwhile, the FCC also allows 174 & 176 as well as 180 & 182 combined with each other to form a 20 MHz channel; however, this is with less immediate interest [29].

Unlike its 802.11a/b/g counterparts, whose channels are treated equally to provide a communication service, implying there is no difference if you choose 1,6 or 11 channels in 802.11b/g, the channels for 802.11p have two kinds, namely Control Channel (CCH) and Service Channel (SCH), according to IEEE 1609 WG. Furthermore, the designers never expect the DSRC device, whether RSU or Onboard Unit (OBU), to be able to access all seven channels; some of them can only access one channel at a time. Simply put, only the very middle channel of 178 is the CCH and the remaining 6 channels are all SCH. Sometimes, people refer to CCH as a safety-oriented channel and SCH for non-safety purposes, which are not very accurate and is only judged on the meaning of the wording, as they figure “Control” must have a higher priority than “Service”. However, according to the definition of IEEE 1609.4, the CCH is reserved for DSRC management frames and short data messages for safety-relevant applications. SCH can be used for either safety or non-safety purposes. On July 20, 2006, the FCC further defined services for 172 and 184 channels, which are the two ones located at the edges of the DSRC band. Under FCC 06-110 2006, channel 172 was sued “exclusively for v2v safety communications for accident avoidance and mitigation, and safety of life and property applications.” Meanwhile, channel 184 is designated as “exclusively for high-power, long-distance communications to be used for public safety applications involving safety of life and property, including road intersection collision mitigation”. Through these definitions, at least we cannot use these two channels for road map updating or travel guide purposes.

3.6 Transmission Power

3.6.1 WLAN Transmit Power Regulation

It is important to understand that there is a transmit power limit on any communication system, either by regional regulation or public health consideration. For instance, the maximum transmit power for a GSM base station (BS) and mobile station (MS) are 20 W and 2 W. One of the most important reasons to put restrictions on MAX PTx (Maximum Power Transmitted) is due to interference. This conception has been heavily deployed in mobile networks, whereby inappropriate transmit power often causes handover failure, cross section coverage or even an isolated island effect. Meanwhile, although we often define a channel in certain precise frequency ranges, which is actually very ideal, all hardware working at a certain carrier frequency will generate a sideband lobe beyond its intentional frequency band. The IEEE defines a transmit frequency mask for the 802.11 family, under which the first sideband lobe, which is ±11 MHz with a width of 22 MHz from the centre frequency of the main carrier frequency, must be at least 30 dB less than the main lobe. Also, any other sideband lobes ± 22 MHz from the central main lobe must be 50 dB lower [30]. Figure 3-10 gives an illustration of a transmit spectrum mask and sideband lobe interference.

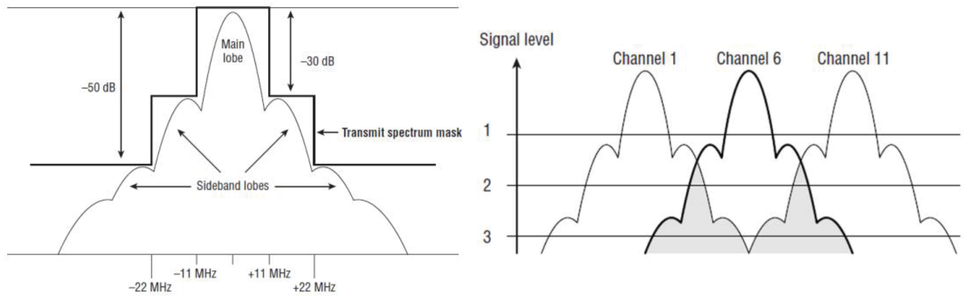

Figure 3-10 Transmit spectrum mask, and side band interference

The term of transmit power limit has dual meanings, including power generated and power transmitted. The former often refers to the power of Intentional Radiator (IR), including all components from transmitter to antenna, but excludes antenna. The latter has a much more popular term (Equivalent Isotropically Radiated Power (EIRP)), which means the highest RF signal strength transmitted from a particular antenna. We can conclude that, if there is no gain for antenna, the power of IR will be equal to EIRP.

The FCC in the United States and controlling entities in other countries set limitations both on power of IR and EIRP for 802.11 standard suites, depending on frequency band and communication methods, i.e. Point to Multipoint (PtMP) or Point-to-Point (PtP). It indicates that the RF designers need to pay attention not only to power emitted by an antenna but also the amount sent to it. Concerning ISM 2.4 GHz band and 5 GHz UNII band for PtMP, the FCC allows maximum power of IR to be 1 W (30 dBm) and EIRP to be 4 W (36 dBm). Figure 3-11 gives an illustration of the power of IR of 5 GHz PtMP regulations.

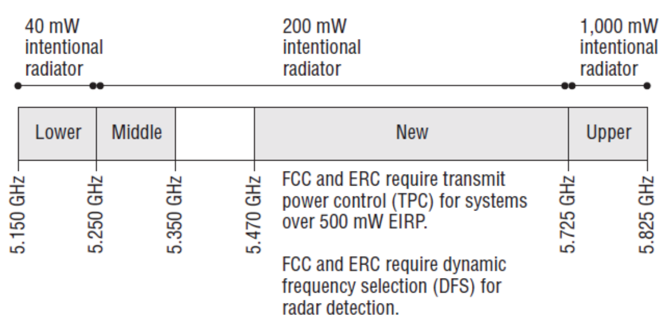

Figure 3- 11 5 GHz Power IR regulations

For 2.4 GHz PtP, the maximum power of IR is still 1 W but the maximum EIRP flexibly ranges from 36 to 52 dBm, according to various powers of IR. The basic rule turns out to be that every 3 dBi gain of antenna needs a 1 dBm reduction from IR. Table 3-2 gives the list of IR and EIRP combination [31].

Table 3-2 IR and EIRP combination at 2.4 GHz UNII of PtP

IR in dBm	Antenna Gain in dBi	Maximum EIRP in dBm
30	6	36
29	9	38
28	12	40
27	15	42
26	18	44
25	21	46
24	24	48
23	27	50

The rules for 5 GHz UNII 1/2 P2P bands are the same as their 2.4 GHz counterparts. However, the FCC treats UNII-3 differently, as it allows a maximum of 30 dBm for IR and 23 dBi for antenna, thus comprising a maximum of 53 dBm EIRP; any extra antenna gain needs to conduct a 1 dBm reduction from IR rather than the 3:1 rule.

3.6.2 Transmit Power Limit on 802.11p

However, the transmit power limit for 802.11p standards is quite different from its 802.11a/b/g counterparts, which is based on several reasons. Firstly, each channel of 802.11p is divided into either CCH or SCH, rather than treated equally. Meanwhile, even SCHs are further designated for different purposes. Secondly, the power limits may vary with entities using it, either private or public; also, the RSU are always considered as public. Generally speaking, public entities, such as police department or road management bureau, are allowed to use higher EIRP than private users on CCH and SCH 184. There are no remarkable differences in the remaining 6 channels, between public and private. On the other side, two channels for short distance communication 180 and 182 have lower power limits than other channels. Private OBUs working on them are allowed a higher power of IR than RSUs and there are no limits defined on public OBUs, which is understandable, since antennae on OBUs generally have less gain than RSUs. Table 3-3 lists detailed power limits for channels of 802.11p standards [32].

Table 3-3 Max Power for IR and EIRP

	All in dBm							
Channel	**Public RSU**		**Private RSU**		**Public OBU**		**Private OBU**	
	Max Power of IR	Max EIRP	Max Power of IR	Max EIRP	Max Power of IR	Max EIRP	Max Power of IR	Max EIRP
172	28.8	33	28.8	33	28.8	33	28.8	33
174	28.8	33	28.8	33	28.8	33	28.8	33
176	28.8	33	28.8	33	28.8	33	28.8	33
178	28.8	44.8	28.8	33	28.8	44.8	28.8	33
180	10	23	10	23	not defined	not defined	20	23
182	10	23	10	23	not defined	not defined	20	23
184	28.8	40	28.8	33	28.8	40	28.8	33

One more thing that needs to be mentioned here is the RSU height. There is restriction on the height of RSU at a maximum of 15 meters. However, the above table is just for height equal or lower than 8 meters, whose excess requests reduction of EIRP correspondingly.

3.7 Wireless Channel Characteristics

3.7.1 Overview

The design of a wireless network requires much more effort compared to the wired ones. The transmission medium for the latter one is generally stable and scalable. For instance, the coated fiber cable definitely would provide extremely high throughput, while affected little by environmental changes. On the other hand, although the cost-free wireless medium is almost everywhere, a designer has to take many more aspects into consideration. The three main factors dominating wireless communication are attenuation, fading and the Doppler effect. The main reason leading to wireless communication complexity is the channel characteristics not just varying according to different radio link technologies, such as working frequency, modulation mechanism, and bandwidth, but also different application environments. That indicates that the overall channel characteristics are the interaction between the nature of transmission systems and changing environments. In short, there is no absolute solution for any wireless system but only better refined approximate ones.

The three factors mentioned above are mainly used to describe the effects based on different attributes of a communication environment. Under fixed radio link technology, attenuation indicates signal loss being mainly due to transmission distance and absorption. Meanwhile, fading subdivided into small and large scale ones is caused by a multipath propagation phenomenon related to surrounding objects. The last Doppler effect happens when there is a relative speed difference between Tx and Rx. They have remarkable impacts on the overall performance of wireless communication but are not always harmful. For instance, in respect to multipath propagation, some Fresnel zones will increase signal strength, thus helping to overcome some path loss [33]. Therefore, different channel models have been brought out and kept in modification in order to better describe the channel characteristics for given wireless communication systems.

802.11p needs to be deployed in a highly dynamic environment and is also time-critical. Therefore, even a channel model fitting 802.11a mainly under a stationary environment for regular home & office usage cannot be applied on 802.11p directly. Although, it is only a modified version of 802.11a; in most cases, there is a noticeable difference between them.

3.7.2 Channel Models for 802.11p

There are various channel models for different types of wireless communication-based and working environments. For instance, the fading component analysis can mainly be divided into Rayleigh and Rician; the former one is for propagation without dominant LOS, and the latter one is used for the opposite case. Empirical path loss models widely adopted in Mobile Phone Networks, such as Okumura-Hata or Walfish-Ikegami, cannot be used for 802.11p directly, due to significant differences in operation frequencies or modulation mechanisms. Among all the proposed models for VANET, two models will be introduced, as follows:

The main general model for the empirical study of VANET channel characteristics can be expressed as follows in dB unit [34],

$$P(d)=P_0 - 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma + Y \quad \text{(Equation 3-1)}$$

P_0 is the transmission power at reference distance d_0 which is often used in WLAN link budget calculation, normally 1 meter distance away from the transmitter antenna. n refers to pathloss exponent. X_σ and Y contribute to large and small scale fading, respectively. The former one has a Gaussian distribution with σ at standard deviation, when modeling in a log-normal variant. Y can be modeled either Rican or Rayleigh..

A Two Ray Path Loss Model takes a LOS dominant signal into consideration. We use the V2V scenario for instance. The received signal is the combination of LOS and reflected signal by the ground. Figure 3-14 illustrates the situation of this model.

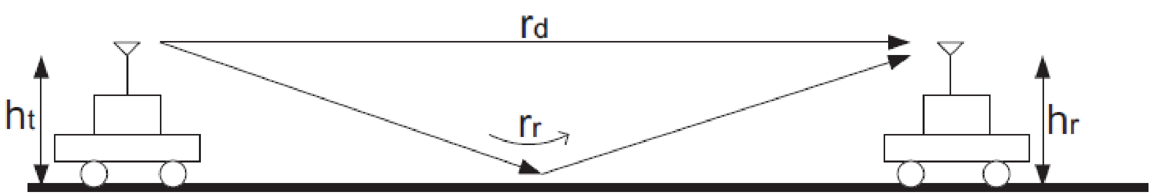

Figure 3-12 Two Ray Path Loss Model

Based on free space path loss, the received signal strength of the two ray model can be refined as follows [35]:

$$P_r=\frac{P_t G_t G_r}{L(r_d)}[D_d\left(\frac{\lambda}{4\pi r_d}\right) + D_r(\frac{\lambda}{4\pi r_r})\eta e^{-j\{k(r_d-r_r)+\phi\}}]^2 \quad \text{(Equation 3-2)}$$

Where the path length of LOS and reflection are annotated as r_d and r_r. η, L and ϕ represent reflection, the coefficient, absorption factor and phase rotation of reflected signal.

3.8 Summary

In this chapter, we gave the reason why IEEE 802.11p is allocated a 5GHz spectrum and analysed its attributes by using 10 MHz for a channel bandwidth. It shows that the modification of PHY and adoption of the OFDM scheme enhance its capability of overcoming undesirable and dynamic communication environments on VANET.

Chapter 4 Medium Access Control and Quality of Service

4.1 MAC Protocol for IEEE 802.11 Standards

4.1.1 Overview

The MAC, as its name implies, refers to the mechanism of accessing the communication medium when there are multiple stations (STAs) operating in the same channel. On the other hand, Quality of Service (QoS) indicates the control mechanism in data networks that tries to ensure a certain level of performance to a data flow, which is in accordance with requests from the application program. These two terms are actually tightly related. In wireless networks, due to their remarkable distinguishing feature, as oppose to their wired counterpart, people makes much more effort on a MAC mechanism in order to achieve better performance.

Generally, MAC protocols can be divided into two main classes: deterministic and random, whose protocols may be either under centralised or decentralised control. Since 802.11p is for a highly dynamic and unpredictable environment, its MAC protocol can only be chosen from a random class rather than a deterministic one. Figure 4-1 provides an overview of various MAC protocols.

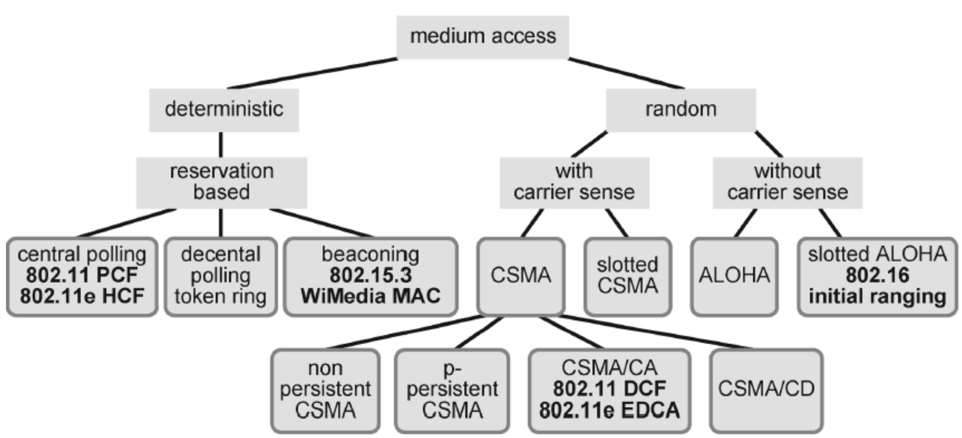

Figure 4- 1 Overview of Different MAC Protocols [36]

4.1.2 Collision Avoidance Mechanism

IEEE 802.11 standards adopt a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to ensure only one device transmits at any one time, in order to reduce that eliminating collisions within their CSMA mechanisms are the same as each other but CA mechanisms might still vary according to different standards. In general, there are three kinds of elements incorporated into each other to perform CA: Interframe Spaces (IFS), contention window (CW) and binary exponential backoff (BEB), and RTS/CTS. The first two are used to provide a double collision guard by letting STA wait for an IFS interval, when sensing the medium is idle rather than transmitting immediately, and extra contention window time for further collision avoidance. The last one is actually optionally deployed to address hidden node problems in WLAN. When STA gains the rights of accessing the medium, instead of sending data frames immediately, it will send RTS in which there is a Duration sub-field to indicate how long the whole process of transmission will last, including at least three intervals of Short IFS (SIFS), one CTS, one Data Duration and one ACK. This makes all STAs in the communication domain of the transmitting device obtain the information about how long the medium will be occupied. The destination STA then sends a CTS also containing duration information of one SIFS and CTS shorter than its RTS counterpart, which will be received by all STAs in the communication domain of the receiving device. The combination of the above-mentioned two procedures eliminates the hidden node problem. Figure 4-2 illustrates these mechanisms.

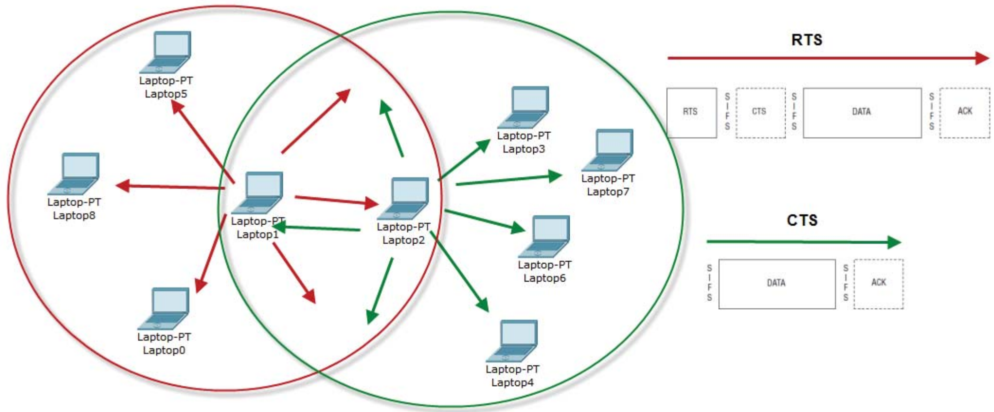

Figure 4-2 RTS/CTS Mechanism addressing hidden node problem

After deciding the CSMA/CA is a basic MAC protocol for 802.11p, from Figure 4-1, we can further see that there are two choices for MAC protocol: 802.11 Distributed Coordination Function (DCF) and 802.11e EDCA. The fact is that, in original 802.11 standards, there are only two medium access coordination functions defined: DCF and Point Coordination Function (PCF). The former is contention-based and is mandatory for a basic service set (BSS) and independent BSS (IBSS) applying 802.11 standards. On the other hand, PCF is an optional, contention-free mode, but it requests centralised topology. Concerning the QoS, 802.11 standards are designed to merely provide a best effort service and also when in shortage of a built-in mechanism for real-time services, which can hardly be used for either throughput or delay-sensitive applications. It implies that both DCF and PCF are not directly suitable to DSRC. Such a situation changed when the Enhancement Task Group in 2005 brought up an approved amendment standard (IEEE 802.11e), in which a set of QoS enhancements for WLAN applications were made by modifying the MAC layer in order to provide differentiated classes of services. In 802.11e, both DCF and PCF enhancements have been made through a new coordination function called the Hybrid Coordination Function (HCF) with two types of channel access mechanisms, EDCA and HCF Controlled Channel Access (HCCA), which evolved from DCF and PCF, respectively [37]. All the above-mentioned became the very reasons why 802.11p chose EDCA to be a MAC protocol for

QoS purposes. However, we need to notice that the EDCA is absolutely not an isolated protocol but instead shares lots of similarities with its ancestor. Figure 4-3 illustrates a brief relationship between these protocols.

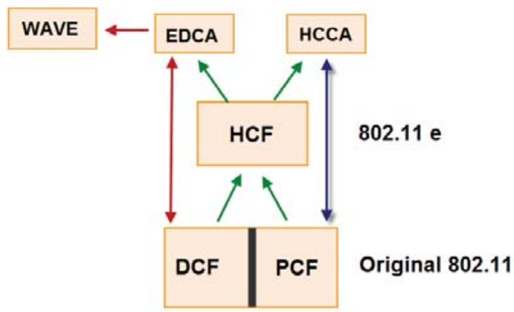

Figure 4- 3 MAC Protocols Relationship

4.2 Enhanced Distributed Channel Access (EDCA)

4.2.1 Introduction of EDCA Mechanism

As mentioned previously, IEEE 802.11 standard was designed to provide experience of an Ethernet-like service over wireless, which is often referred to wireless Ethernet by virtue of supporting a best-effort service. On the other side, the 802.11p MAC layer for QoS purposes should focus on the prioritisation of important safety and time-critical messages, whereby making the application of normal 802.11 standards impractical. Since 802.11p is a cross-layer protocol, its PHY is similar to 802.11a and the MAC layer adopting EDCA proposed by IEEE 802.11e for QoS guarantee. Note that the term of enhanced DCF (EDCF) is used instead of EDCA, as it evolved from DCF in an earlier version of 802.11e draft [38].

The 802.11e is an approved amendment standard which was brought up by the Enhancement Task Group (TG) in 2005, whereby a set of QoS enhancements for WLAN applications was provided by modifying the MAC layer and also offering differentiated classes of service. Actually, the most well-known technology adopting 802.11e is Wimax. Besides providing an enhanced MAC mechanism, there are also two kinds of QoS defined in 802.11e, namely prioritised and parameterised QoS [39]. The parameterised one is also a strict requirement quantitatively, and obviously 802.11p is only capable of providing former ones, under which frames arriving at the MAC layer would be labeled as different user priorities by the upper layer and differentiated channel access will be performed. It is understandable that the frame with the highest priority will be sent through the channel first. There are two main remarkable conceptions in 802.11e, thus distinguishing it from DCF or PCF, which is stated as follows:

A Traffic Identifier (TID) is a value in a MAC service data unit (MSDU) ranging from 0 to 15. The value from 0 to 7 indicates user priority of the frame, whereby 7 is the lowest priority. Meanwhile, the value from 8 to 15 is used to identify which traffic stream the frame belongs to and these are often called traffic stream identifiers (TSIDs). There are eight different TSIDs that can be assigned on each traffic stream, which means that 8 TSs per station can be achieved [40].

Transmission Opportunity (TXOP) is a bounded time interval when STA is permitted to send a series of frames which define when STA can transmit and what the maximum transmitting duration is (TXOP limit). A TXOP obtained from EDCA contention is called EDCA TXOP. The value of a TXOP limit is determined by the AP, according to the rules of the channel access schemes and is informed to all STAs through beacons. In short, TXOP adoption makes the transmission time for each STA more controllable and predictable, together with the enhancement on protocol.

As mentioned earlier, there are eight respective values ranging from 0 to 7 of user priority (UP) in each MSDU. The MAC layer will categorise each frame into its corresponding access category (AC) according to its UP value. The AC acts as a banner for the common set of EDCA parameters adopted by STAs for channel contention purposes.

The EDCA defines four ACs, namely AC_BK (Background), AC_BE (Best Effort), AC_VI (Video) and AC_VO (Voice traffic) [41]. The mapping relationships between eight UPs and four ACs can be found in Table 4-1, as follows:

Table 4-1 UP's map to ACs

Priority	User Priority (UP)	Access Category	Designation (Informative)
Lowest	1	AC_BK	Background
	2	AC_BK	Background
	0	AC_BE	Best Effort
	3	AC_BE	Best Effort
	4	AC_VI	Video
	5	AC_VI	Video
	6	AC_VO	Voice
Highest	7	AC_VO	Voice

There is an interesting fact drawing our attention when reviewing the table; UP 0 is the default UP value with the lowest priority within eight value groups. However, its corresponding AC priority is higher than its counterparts of UP 1 and UP 2, which are for background services providing support to applications without the need to process the data immediately and thus possess the lowest priority. On the other hand, AC_VO is with the highest priority and should be used for all management frames. Figure 4-4 illustrates the EDCA mechanism at a MAC layer.

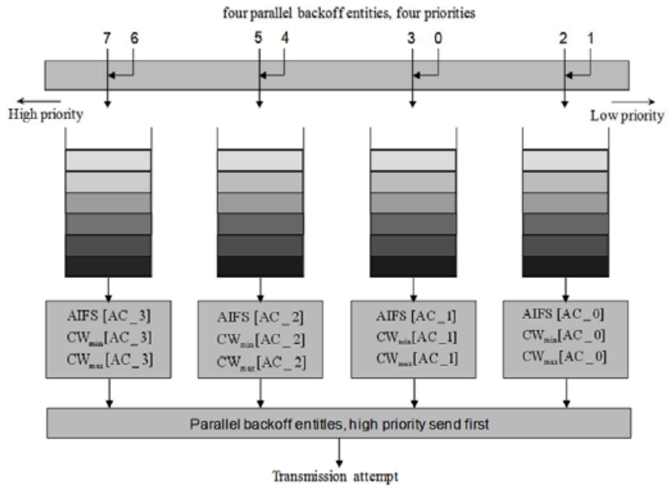

Figure 4-4 EDCA mechanism at MAC layer

By reviewing the above figure, we can see that there are four queues in which different enhanced distributed channel access functions (EDACFs) are deployed according to AC. Meanwhile, each EDCAF with its own Arbitrary Inter Frame Space (AIFS) acts as a single enhanced DCF entity. It then performs an internal contention mechanism, i.e. handling collision in virtual manner and sends the frame with the highest priority after selection. Other EDCAF therefore do a backoff with increased contention window values. In general, EDCAF belonging to certain AC uses content media resources by using AIFS[AC], CWmin[AC] and CWmax[AC]. AIFS[AC] is calculated as follows:

AIFS[AC] = SIFS + AIFSN[AC] x SlotTime (Equation 4-1)

Concerning 802.11p, SIFS and Slot Time are 32 and 13 µs, respectively [42].

AIFSN[AC] defines according to two rules: if this is an access point (AP), and if its value is an integer greater than zero. For STA, the value should be greater than one. This is one of the most remarkable characteristics in EDCA, whereby the Interframe spacing is flexible.

Furthermore, the extended inter-frame space (EIFS) for each AC is determined as follows:

EIFS[AC] = EIFS – DIFS + AIFS[AC] (Equation 4-2)

Figure 4-5 shows AIFS and Backoff time contend for channel access in EDCF

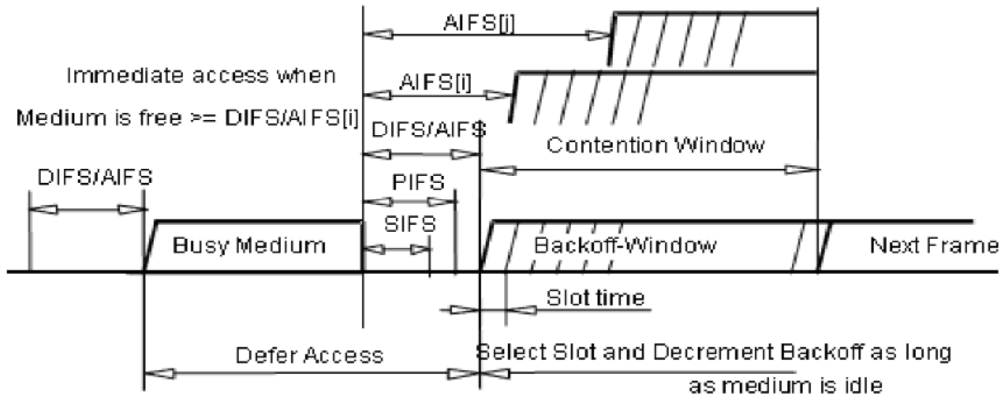

Figure 4- 5 AIFS and Backoff Time Contend for Channel Access in EDCF

4.2.2 EDCA for 802.11p

As IEEE 802.11p is designed exclusively for a Vehicle Environment, it adopts EDCA, while maintaining some modifications. Multi-channel operation is the main difference of 802.11p at a MAC layer from its counterparts, where all channels (CCH and SCH) are provided a set of traffic categories for QoS guarantee purposes. Figure 4-6 provides an illustration of an EDCA mechanism at 802.11p MAC layer.

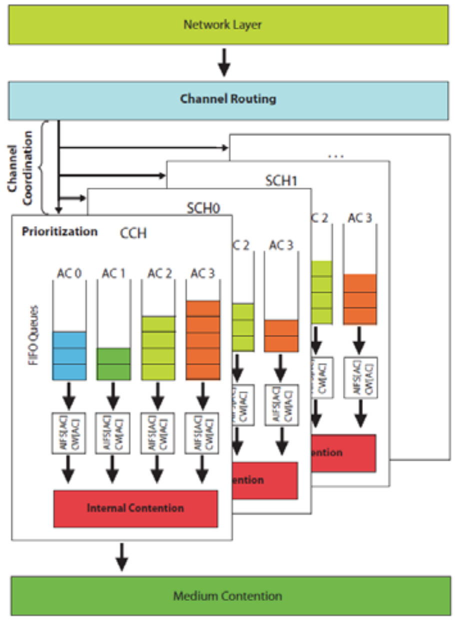

Figure 4-6 EDCA at 802.11p MAC [43]

There are still four ACs labeled from AC[0] to AC[3]. Under the CCH interval, each one can be possibly explained, as follows:

AC[3]: with the highest priority, it is used for emergency information, especially for collision avoidance application. Other instances can be obstacles, e.g. wet road surface, traffic light break down.

AC[2]: concerns presence and speed information broadcasted by vehicles.

AC[1]: concerns the information from other vehicles for help, but is not strictly related to safety issues.

AC[0]: concerns information aimed at establishing new non-safety-related connections via SCHs.

However, we need to notice that the 802.11p standard was just finalised and that its application is still being processed. The definition of each AC, either on CCH or SCH, will largely rely on upper layers, especially the application layer designed by different manufacturers and thus may be various.

Meanwhile, as 802.11p is used for time-sensitive application for safety purposes mainly and because CCH and SCH are all allowed to perform real-time traffic, it is obviously beneficial if we assign more time to CCH. However, for the sake of overall satisfaction, the tradeoff of time allocation of the QoS guarantee mechanism has to be made in order to cope with large and regular data traffic on SCHs, whilst meanwhile keeping CCH delay at an acceptable range. According to what is mentioned above, each AC represents a specific EDCAF at the MAC layer, which is further defined by corresponding parameters. Apparently, these EDCA parameters, even with the same AC, will vary in different channel types. There are two adaptive forms at IEEE 1609.4 for CCH and SCH, respectively, as shown in Table 4-2 and Table 4-3.

Table 4-2 EDCA parameter for CCH [44]

AC	Traffic Type	CWmin	CWmax	AIFSN
AC1	background	15	511	9
AC0	best effort	7	15	6
AC2	video	3	7	3
AC3	voice	3	7	2

We can see from the above table that the AC1 is actually with the lowest priority not only with the biggest CWmin and CWmax within the whole table but also the highest AIFSN, which indicates its AIFS and backoff window will be the longest one. Meanwhile, AC0 is at the middle priority among its counterparts, whose CWmin is just the CWmax of AC2 and AC3 but AIFSN is doubly comparing with AC2. Concerning AC2 and AC3, with the same contention windows, their AIFSN has only 1 slight difference ensuring AC3 is the top priority.

Table 4-3 EDCA parameter for SCH [44]

AC	Traffic Type	CWmin	CWmax	AIFSN
AC1	background	15	511	7
AC0	best effort	15	511	3
AC2	video	7	15	2
AC3	voice	3	7	2

In contrast to Table 4-2, we can see that the EDCA parameter for SCH is more loosened than what is applied on CCH. However, the AC3 for SCH at the highest priority is exactly the same as its counterpart of CCH, maybe because SCH sometimes involves safety-oriented application. There is a tradeoff between AIFSN and the contention window made in SCH. As the AIFSN in SCH are all lower than their corresponding ones in CCH, it indicates that all AIFS in SCH will be shorter than CCH, except AC0. Such a mechanism makes nodes get ready to send frames by quickly entering into the backoff stage. By shortening the AIFS, the collision probability might increase but it will be accepted as the deployment happens in SCH, rather than strictly related to time-critical transmission. At the same time, the contention windows, both min and max for SCH ranging from AC1 to AC2, are all greater than CCH, which compensates for the shortcoming, due to the related lower AIFSN. For instance, The CWmax value of AC0 in SCH proving the best effort traffic type is set at 511, which means that EDCAF here is willing to ensure transmission reliability by doing retransmission and waiting longer, in order to have ACK. To be more specific, Figure 4-7 illustrates the AIFS plus minimum backoff time for each AC in both channels.

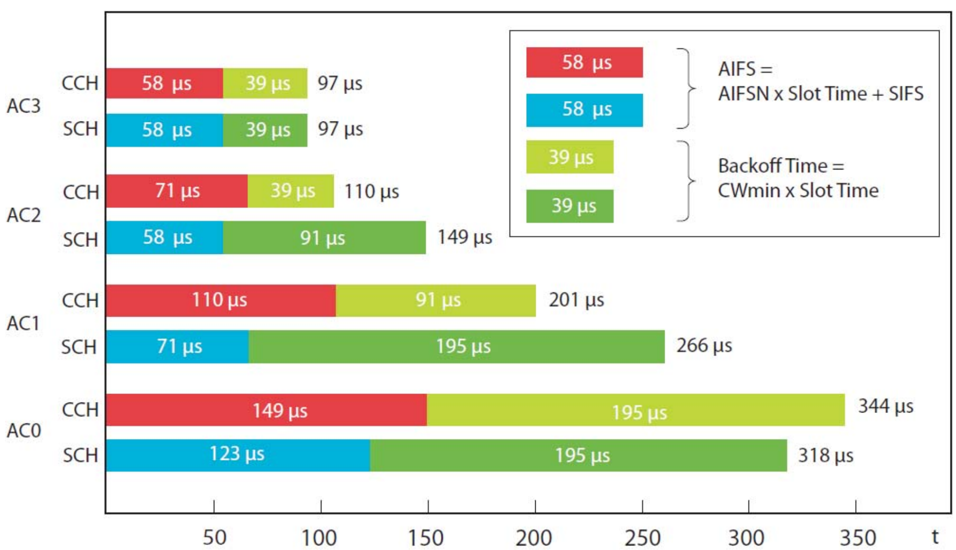

Figure 4-7 AIFS and Backoff Time for CCH and SCH [43]

Since the channel environment for transmission is unpredictable, only minimum backoff time can be given, since it is irreverent to the transmitting situation. The time parameter on the chart matches what was mentioned previously. The time intervals of AIFS and backoff time for the highest priority in both channels are the same. Followed by the AC2 and AC1, their AIFS values in CCH are longer than SCH but backoff times are in a contrary situation, which makes the total time interval shorter than SCH. The last AC0 turned out to be a bit different, due to the same minimum backoff time in these two channels.

4.3 MAC Protocol Data Unit of 802.11p

The structure of a MAC protocol Data Unit (MPDU) is quite a delicate and complex part of 802.11 standards, based on the fact that a MAC layer carries out most functions in WLAN communication, which generate a MPDU by wrapping MSDU received from LLC and then handing to the PLCP sublayer in PHY, as mentioned previously.

In fact, there are four types of frames in 802.11, namely management, control, data and reserved; however, an overall MPDU format is generally given regardless of frame type, since the structure remains the same across all frames, even though not all parts are used in every specific type. Meanwhile, the MPDU format can be further divided into two kinds - QoS supportive and non-supportive - which implies that the format of 802.11p will be the same as 802.11e, with an additional QoS field than normal 802.11 a/b/g standards. Figure 4-8 illustrates the overall MPDU format.

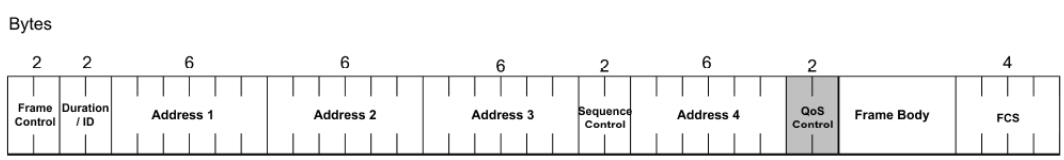

Figure 4- 8 Overall MPDU Format of 802.11p/e

A brief introduction for important fields/subfields shown above will be given as follows:

Frame Control: This 2 bytes long field is the most complex one in MPDU and can be further divided into several sub fields shown in Figure 4-9.

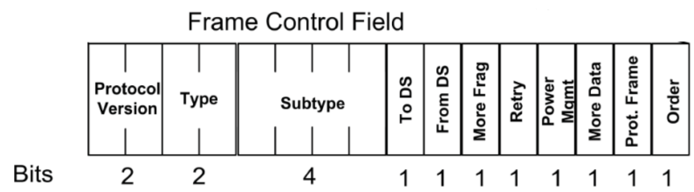

Figure 4- 9 Sub-fields of Frame Control

Currently, the protocol version is 00 and the remaining possibilities are reserved for future use. Frame types are used to indicate four types of frames, as mentioned above. Table 4-4 details the type field instance.

Table 4-4 Type Field Instance

Bits	Frame Type	Example
0,0	Management	Association, Authentication, Probe
0,1	Control	ACK, CTS, RTS
1,0	Data	
1,1	Reserved	

Furthermore, the sub type field indicates the specific type of frame, for instance, 0000, 1010 and 0001, mean association request, Power Save (PS)-Poll and Data +CF-ACK, respectively. As we know, fragmentation can be used in WLAN communication to support the division of MSDUs into smaller elements carried out by More Frag Field set to 1, if there is a fragment subsequently belonging to the same MSDU. However, it is necessary to point out that only unicast frames will be fragmented rather than broadcast or multicast frames. In this case, the MAC protocol will use the aFragmentationThreshold parameter in its management information base (MIB) to judge whether the size of generated MPDU will exceed the threshold by merely passing the whole MSDU to the MAC layer. If the answer is true, then fragmentation will be conducted in order to break down MSDU and send each one separately.

1. Duration/ID and Address Fields: The former field lasting 16 bits long contains information of NAV or short ID alternately. However, since only the power-save poll (PS-Poll) uses a short ID tightly related to the PCF mechanism, this field is generally representing duration for 802.11p application, under which Bit 15 is set to 0 and maximum value 32767 in microseconds can be obtained by manipulating Bit from 0-14. The four MAC address fields in MPDU are selectively used according to different types of frames. In most cases, only addresses 1-3 contribute wireless communication and address-4 is only for special situations, such as DS, which is also the reason why it does not adjoin with the other three counterparts in MPDU. In short, Addresses-1/2 are always the recipient/ destination addresses or the under ToDS/ FromDS addresses of AP, respectively. Address-3 is generally the missing address, since under BSS, merely indicating an address of AP is not enough and an extra field needs to be used for the source or destination address. However, we can predict that in case there are two APs in DS, the communication has to account for the full usage of four address fields. Beyond that, a higher layer address mechanism, such as IP, will be needed. Under the 802.11p scenario, only addresses 1 and 2 join the procedure of communication in most cases.
2. Frame Body and QoS Control Fields: The frame body often referred to MSDU is passed from higher layer LLC. In fact, it is a bit difficult to find the maximum size of MSDU in 802.11 standards, due to the evolution and advancement. This can be explained twofold. Firstly, the 802.11-2007 standard defines that the maximum size for MSDU is 2304 bytes for non-security mechanisms applied or 2312 (WEP)/2324 (TKIP) [45] as overheads are increased. Thus, the derived max length has three possibilities, namely 2338 (non-security), 2346 (WEP), and 2358 (TKIP). Under the QoS supported Frame structure, another 2 bytes need to be added on the above results, thus making the theoretical maximum length 2360. On the other side, PSDU allows a 4095 maximum in length [46], although MPDU can only reach half of the size. It is not correct to mark MSDU at 4095, as it violates the 802.11-2007 definition. Secondly, the

latest 802.11n brought up two novel schemes - aggregate MSDU and MPDU (A-MSDU, A-MPDU) – which extended the maximum sizes to 3839/7935 and 65,535 octets, respectively [47]. Based on what is stated above, we can conclude that the max MSDU for 802.11p should be less than 2304, due to no authentication mechanism required. Concerning the QoS control field, which is 16 bits long and which bit 7 is reserved, the first 3 bits are used to indicate TID and bit 4 is for End of service period (EOSP) purposes, through setting 1 for transmission/ retransmissions, or 0 otherwise. Bits 5-6 define the acknowledgement policy under different communication procedures. Finally, multi-functions are carried out by Bits 8-15, in general, TXOP limit, QAP PS Buffer State, TXOP duration requested and Queue size.

4.4 Summary

In this chapter, we introduced the mechanisms of MAC protocols for IEEE 802.11 standards. Meanwhile, 802.11p adopts EDCA as a more advanced one revolving from DCF, which is not only for collision avoidance but also for concentrating on providing QoS. Its traffic stream is granted different EDCAF according to its TID out of four kinds or channel types (CCH or SCH) in order to provide a priority-oriented service. Also, the structure of MPDU of 802.11p has been reviewed.

Chapter 5 VANET Topology and WAVE Short Message

5.1 Multi-Channel Operation`

Due to the nature of DSRC, it needs to tune to CCH and SCHs alternately. By reviewing the DSRC protocol suite given in Chapter 2, we can see that the MAC layer of DSRC is divided into two sub-layers. The upper MAC layer, which is defined by IEEE 1609.4, is mainly used for three functions related to multi-channel operation, namely channel coordination, channel routing and User Priority. The lower one focuses on wireless medium access. Such division is a very unique characteristic of DSRC, thus distinguishing itself from its counterparts, such as 802.11a/g, as they only work in certain operational channels, whose MAC structures are relatively simpler than their DSRC counterparts.

Even though IEEE Std 1609.4-2010 allows one or more PHY devices to be equipped on vehicles, it only provides examples and guidelines for a single-PHY device case under one CCH and SCH. Figure 5-1 gives an illustration of the 1609.4 channel access mechanism.

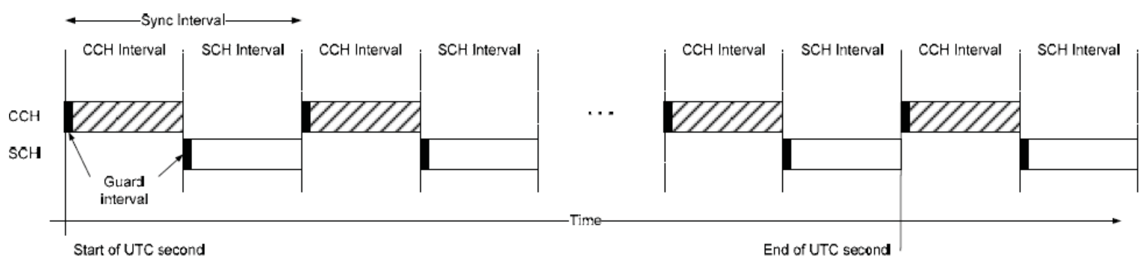

Figure 5-1 1609.4 Alternating Channel Access Mechanisms [48]

The combination of CCH and SCH intervals is called Sync interval, as defined by 50ms each. Moreover, we notice that there is a guard interval (2ms) used to address radio switching and timing inaccuracies among different devices. In VANET, CCH is used for the exchanging of management information, such as WAVE Short Message (WSM) and Service Advertisements. Therefore, it is mandatory for all RF devices to monitor this channel at the same time in most cases. However, it is apparent that such an even division access mechanism cannot meet the requirements of relatively heavy data transmission, as there is no need to always allocate half the length of Sync to CCH for short message exchange. On the other hand, SCH can also be used for traffic safety communication rather than CCH only. Therefore, IEEE 1609.4 actually gives four possible access choices: continuous, alternating, immediate and extended, thus representing different combination types of CCH and SCH according to different applying environments. The first access choice refers to always monitoring either CCH or SCH, which is a special scenario because, at that time, SCH is capable of sending WSM, despite it being optional. Meanwhile, the last two choices will prolong the SCH interval, while also shortening the CCH interval. Figure 5-2 shows these four access mechanisms.

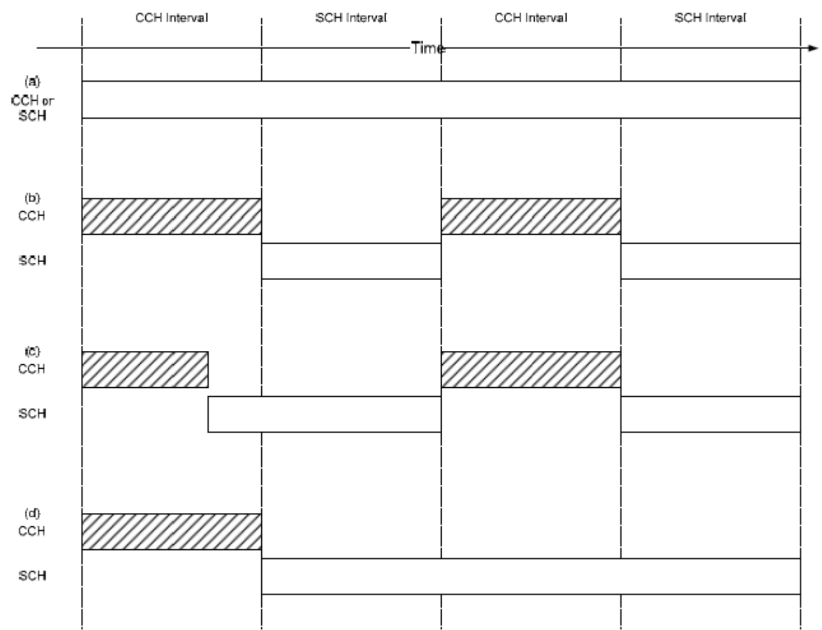

Figure 5-2 Channel access options: (a) continuous, (b) alternating, (c) immediate, and (d) extended

5.2 Characteristics of VANET Topology

5.2.1 Broadcast Mechanism on CCH

Due to the multi-channel operation nature of WAVE communication as well as its highly dynamic environment, its network topology is quite different from 802.11 standards and is much more complex. Meanwhile, we should selectively adopt traditional WLAN topologies in order to understand VANET, rather than just matching them with each other. First and foremost, 802.11p std-2011 clearly defines “communicating data frames outside the context of a BSS” and that the main purpose of V2X communication is for traffic safety that is based on the broadcasting on CCH in general, which indicates that every RF device nearby can exchange such messages. It is irrelevant as to whether OBUs or RSUs should consist of a service set first or not, as the broadcasting uses a wildcard MAC address by setting 0xFFFFFFFFFFFF [49] . The conception of broadcasting may be popular in wired networks, since routers are able to filter the broadcast packets for safety issues. However, the wireless medium is a typical shared medium, which is analogous to a hub rather than a switch, not to mention a router. Heavy broadcasting will cause broadcast storms and will severely impact the throughput of networks. Therefore, the normal IEEE 802.11 standard places a restriction on the broadcasting functionality, which can be only used for beacon or probe purposes. Figure 5-3 provides an example of a broadcast storm in both wired and wireless networks.

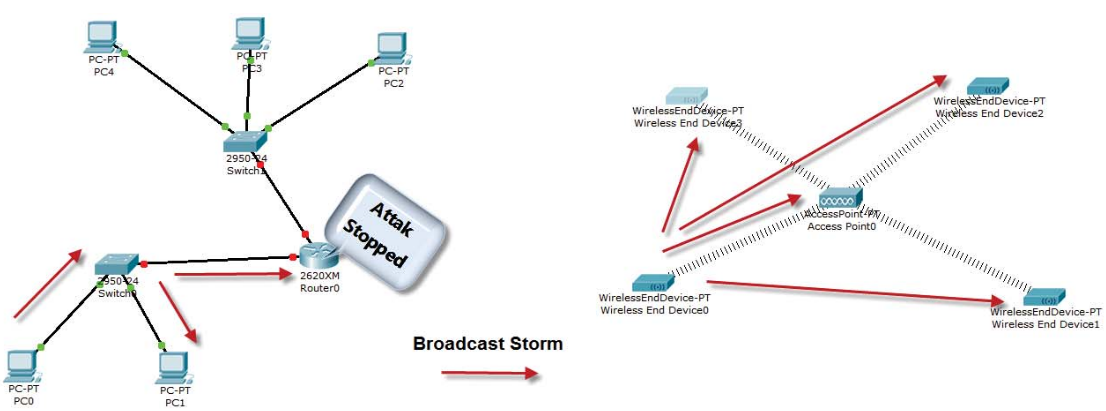

Figure 5-3 Broadcast Storm in Wired and Wireless Networks

5.2.2 WAVE Basic Service Set (WBSS)

As long as we remember that the nature of WAVE communication is for broadcasting on CCH generally, the remaining communication for services rather than safety purposes can additionally happen on SCHs. In this case, RF devices equipped on OBUs or RSUs have to consist of a WAVE Basic Service Set (WBSS) [50]. From this point-of-view, we should realise that the V2X communication can be based on non-WBSS and WBSS, which are able to exist simultaneously. The non-WBSS is the main topology category for broadcasting purposes only, whereby STAs may consist of a WBSS for SCH communication; however, it is not mandatory. Figure 5-4 depicts this situation.

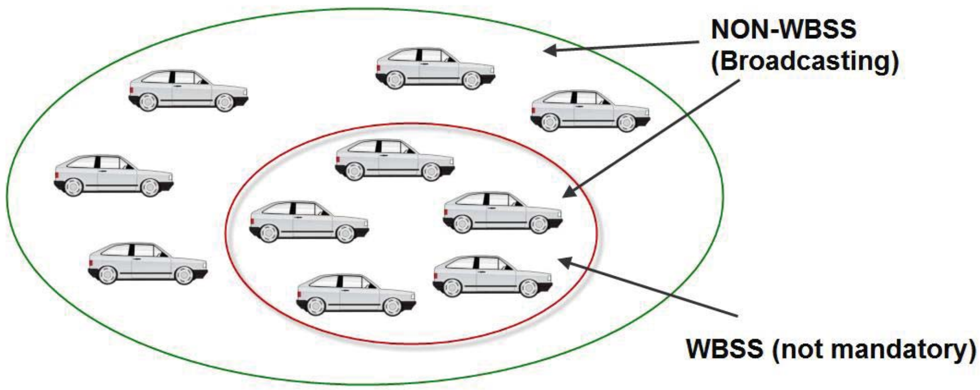

Figure 5-4 Non-WBSS and WBSS Topology

Concerning WBSS, we should not use traditional WLAN to understand it. In some journals, there is usage of the term 'WAVE IBSS' (WIBSS), whereby the author tries to analog WBSS and WIBSS to BSS and ad-hoc networks, respectively [51]. Personally, I do not quite agree that methods, such as the inner mechanism of VANET, are remarkably different from normal WLAN topology. This is based on several facts:

1. There is no access point in VANET, but only service provider and client. Since RSU is a stationary device and is often with high throughput, people often mistakenly take it as an AP. However, in a distribution system, all STA traffic should go through a portal device, i.e. AP, which is totally not the case in VANET. In a WBSS, even RSU acts as a service provider, while OBUs can still perform point-to-point communication. Meanwhile, the communication duration between RSU and OBU is actually very short, whose mean estimate is only 3.6 seconds [52]. Thus, it is more appropriate that we treat RSU and OBU equally in order to be all SATs without

differentiation.

2. There is no authentication or association procedure in WAVE Communication [53]. In a normal WLAN scenario, there are a lot of procedures in association, and much more in authentication. For instance, under passive scanning, the AP will keep sending a beacon at an interval around 0.1 or 0.2 seconds. STA captures this beacon and sends an association request. AP then sends back an association confirmation frame and awaits ACK from STA. Such a procedure is too time-consuming and is not compatible with WAVE Communication. Security issues brought up by eliminating such a procedure are expected to be addressed by a higher layer rather than PHY or MAC.
3. WBSS is ephemeral and is a dynamically organised topology. Unlike BSS or even IBSS, whose network topologies are quite stable and rarely change, WBSS is occasionally generated when a SAT would like to be a service provider by sending a WAVE Service Advertisement frame on CCH. Other SATs receive this frame and hand it to an upper layer in order to decide whether it joins or not. Meanwhile, even STA would have already become a member of certain WBSS; the termination of membership is allowed to happen anytime, without any interaction with the service provider. Since the formation of WBSS is just for services in a very short-term duration and because every STA has the right to be a service provider for a certain application, the WBSS is thus a very unstable and loose topology without any restriction on the number of members and lasting period.

5.3 WAVE Short Message Protocol (WSMP)

5.3.1 Introduction

From Figure 2-1, we can see that there are two kinds of protocol suites sitting in the higher layer, namely WSMP and IPv6 suites [54]. The former is exclusively for time-critical and safety-oriented communication in WAVE, without the need for an IP addressing mechanism, since it is always broadcasted on either CCH or SCH. On the other side, the latter (IPv6) can only use SCH to perform the communication. Figure 5-5 shows these two protocols in a working situation.

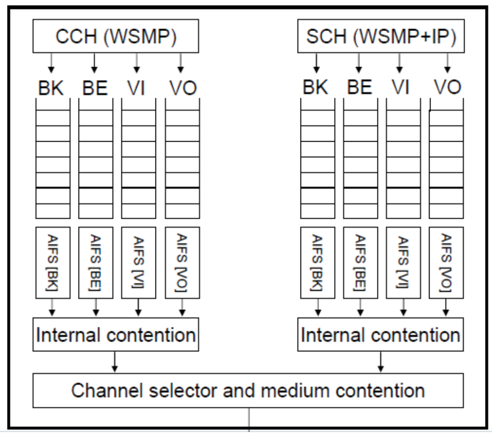

Figure 5- 5 WSMP and IPv6 working on different channels

WSMP, as defined by IEEE 1609.3, is the key to WAVE communication and plays an important role in WBSS formation. It is used for two kinds of message transmission: WAVE Service Advertisement (WSA) and WAVE Short Message (WSM) [55]. When an STA would like to become a service provider, it will first send a WSA, including a provider service ID (PSID), channel number, data rate, etc. After receiving this WSA, a WAVE Management Entity (WME) will check whether the announced application is of interest to any locally registered user applications. If the PSID matches, it is the responsibility of the user application to decide whether to join or not into the announced WBSS, according to application registration parameters. In the first case, the WME will generate necessary MAC primitives and will set any other appropriate configuration at a lower layer in order to join WBSS. A simple procedural flow is illustrated in Figure 5-6.

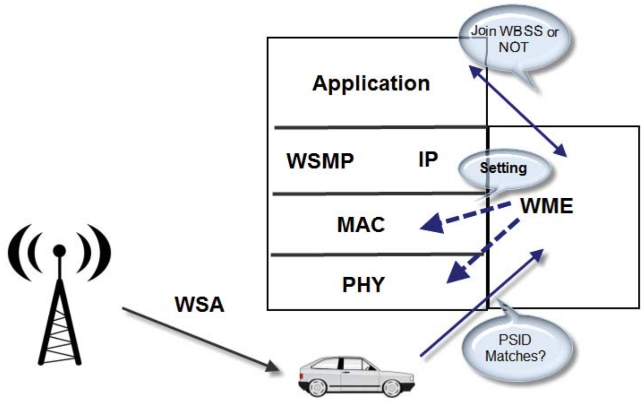

Figure 5- 6 Simple Procedure Flow of WBSS Joining

5.3.2 Frame Format of WSA

There are two kinds of WSA formats: secured and unsecured. Concerning the unsecured one, it consists of three fields, namely Protocol Version, Type and Wave Service Advertisement. Meanwhile, there are an additional two fields (Security Header and Trailer) for the secured WSA format. Within all fields, the Wave Service Advertisement is the most complicated part, including many sub-fields with various lengths in octets. In general, this field can be subdivided into four smaller parts: header, service info, channel info and WAVE Routing Advertisement [56]. Figure 5-7 shows the format.

WAVE version/ change count	Extension fields	Service Info	Channel Info	WAVE Routing Advertisement

Figure 5- 7 Format of Wave Service Advertisement Sub-Field

The header includes one mandatory octet field, together with optional extension fields. Within one octet, the first five bites are used to indicate the WSA version, which is currently set to 1, and the last two bytes, as change count is used by numbering the WSA frame in order to let the receiver decide whether this is the repeated WSA. The extension field is not mandatory but should not exceed 255 octets, as restricted by IEEE 1609.3-2010. The first is the repeat rate, which is 8 bits long and which indicates the sending rate of WSA for a broadcasting service every 5 seconds. The receiver should use this field to evaluate link quality, which is followed by "Transmit Power Used", "2DLocation", "3DLocationAndConfidence", "Advertiser Identifier" and "Country String", which function as their names imply.

Referring to the Service Info field, it provides information of an application service, with a unique PSID for each one, which implies that this field can be repeated when more than one application is provided. 1609.3 allows 0 through 32 instances of this field in the WSA. Figure 5-8 illustrates the format of this field.

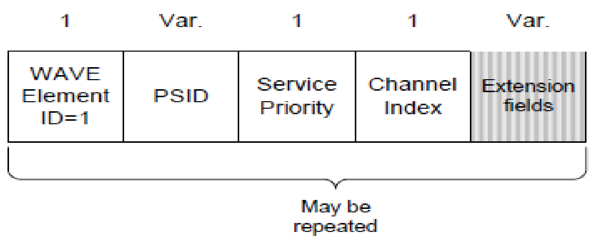

Figure 5- 8 Service Info Format

As we know, DSRC is a typical priority-oriented communication; channel access and service evaluation, both at Rx and TX, are all based on it. Thus, the "ServicePriority" field is adopted for this purpose, which is 8 bits long and which provides 64 degrees of priority level – 0 being the lowest. Moreover, there are some interesting fields in the extension field (also not exceeding 255 octets). For instance, there is a 128 bits IPv6 address and Provider MAC address for traditional IP-based communication. Concerning the RCPI Threshold field in 1 octet long borrowed from IEEE802.11k, it ranges from 0 to -110 in dBm and provides a recommendation to be received for a discarding decision.

The Channel Info field is a relatively fixed-length segment; 6 out of its 7 sub fields are all 1 octet in length and only have exception in the extension field. Furthermore, there shall be 0 to 32 instances of Channel Info segments in the WSA. Each indicates the characteristics of one channel, which is associated with zero or more Service Info and which contains the fields. Within these sub fields, some of them are especially important to WAVE communication. Figure 5-9 provides the format of Channel Info.

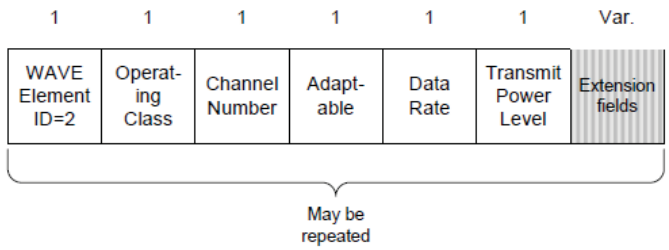

Figure 5- 9 Format of Channel Info

For instance, the Channel Number indicates the number of the channel to which the accompanying information pertains. As we know, DSRC is a multi-channel operation; the procedure of joining WBSS only relies on receiving WSA without any further interaction. The STA, belonging to certain WBSS, has to know which SCH out of six is used to provide the application service and therefore can monitor this channel at its interval. Meanwhile, the Transmit Power Level represents the actual power in the output of the antenna connector for transmission on associated channels. The extension field of Channel Info contains two sub fields. The first one (EDCA Parameter Set) is adopted for QoS purposes. Since there is an inner contention mechanism at MAC of DSRC, this field will include important parameters, such as AIFSN, CWmax, CWmin and TXOP Limit, for each application provided. The second segment of the extension field is Channel Access, which indicates the times in terms of channel interval, during which the provider is on the associated SCH. If set to 0, it will be considered as continuous access, both on a CCH or SCH interval. Otherwise, if set to 1, the provider will be on an SCH interval, only as alternating access.

The final segment of WSA is WAVE Routing Advertisement (WRA), which is also an optional choice. As its name implies, WRA is used to provide information about infrastructural internetwork connectivity, in order to let receivers join the advertised IPv6 network. The adoption of IPv6 is one of the remarkable characteristics of WAVE communication, which can be divided into two logical parts. The first 64 bits, which represent the global routing prefix, and the remaining 64 bits are called host interface identifiers, which are created by using the MAC address of a host interface or random generation number if privacy is concerned. More than a decade ago, network engineers started worrying about the exhaustion of IPv4 addresses and were thus researching a 128 bit long IPv6 addressing mechanism, which was supposed to provide 3.4 $X10^{38}$ and ultimately provide a resolution to that issue. In February 2011, the Internet Assigned Numbers Authority (IANA) assigned the last top level (/8) block of IPv4 to 5 regional internet registries (RIR). However, since the prediction of exhaustion was largely relying on the stage of internet development, the recent and future explosive increase of internet users and providers drastically shortened that deadline. According to the research of the UN's Telecommunications Agency, there were two billion internet users in 2011, not including other industrial regions that require IP addresses, such as GPRS. If we had not adopted technologies, such as classless routing or network address translation (NAT), the exhaustion would happen. Figure 5-10 illustrates the format of WAVE Routing Advertisement.

1	2	16	1	16	6	16	Var.
WAVE Element ID=3	Router lifetime	IpPrefix	Prefix length	Default gateway	Gateway MAC address	Primary DNS	Extension fields

Figure 5- 10 Format of WAVE Routing Advertisement

The Router Lifetime is two bytes long and indicates the duration of validity of the Default Gateway and associated information. Meanwhile, the Default Gateway contains a 128 bits long IPv6 address of the router for SCH communication. The extension field contains a Secondary DNS and Gateway MAC address, which all allow the service to function. All these structures mentioned are for the purpose of providing regular IP connectivity and for eliminating the boundary between data communication for WAVE and internet access.

5.3.3 Frame Format of WSM

The WAVE Short Message is exclusively used for CCH control information, which is related to traffic safety purposes and which should be distinguished from WSA. The generation of WSM is from a high layer to MAC, via different primitives with different headers and tails at different layers. However, due to the nature of WAVE, this mechanism will be quite different from traditional WLAN standards. Figure 5-11 shows the generation of the WSM package.

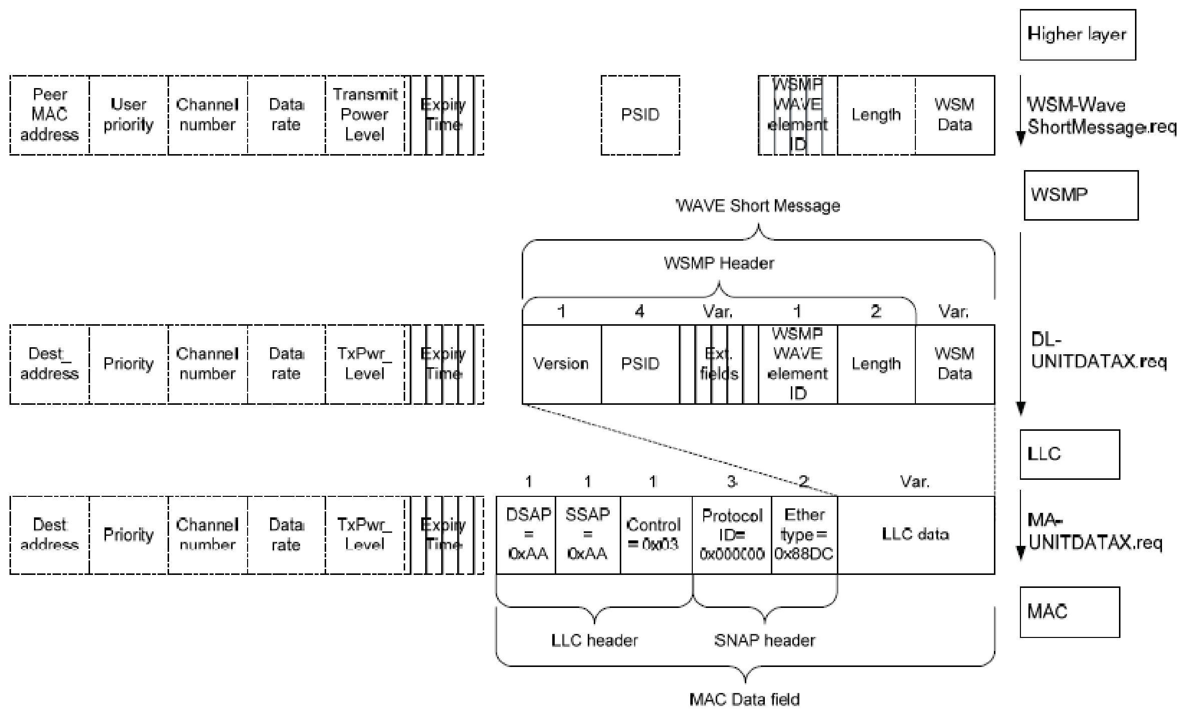

Figure 5- 11 Generation of WSM Package [56]

As we can see from the above figure, the header of the WSM package is the same at a different layer starting from a higher layer; this is unlike a normal WLAN lower layer, which will put its own header and will wrap a higher layer frame into its payload area. This phenomenon is due to important information, such as Destination Address, priority and TxPow_Level, which are decided by the application and which are sent down as separate parameters in the primitive form, rather than as part of WSM. The WSM passing through LLC will finally be put in the LLC Data segment of the MAC Data field, together with an LLC header and SNAP header.

The WSM can be further divided into six segments, whereby the extension field is optional and the length of WSM Data varies. The one octet version field includes a first 4 bits reserved for future usage and the remaining indicate the WSMP version, followed by the PSID field, like WSA. Actually, since WSA and WSM both rely on a WSM protocol, their format structures share lots of similarities. In the WSMP header extension field, it also includes segments, such as channel number, Data Rate and Transmit Power Used, in order to increase the communication performance in WAVE. Concerning the length field, which is 16 bits long and which indicates the WSM size in length, only 12 out of 16 bits are used currently and the remaining 4 bits are reserved. Based on this, we can conclude that the current maximum length of WSM is 4095 bytes, which is actually pretty long compared to most wired and wireless standards. Generally, the TCP/IP protocol, which is based on Ethernet, can only allow 1500 bytes at most and is called the maximum transmission unit (MTU); it totals 1518 bytes when adding a header and the Cyclic Redundancy Code (CRC) [56]. There is no problem for the 802.11 family to handle this, as their payload can take 2304 bytes and is big enough for a distribution system. Meanwhile, people would like to increase the wireless MTU; it can hardly be carried out not only because of current applications counting on the TCP/IP suite for networking but also the infeasibility of setting the MTU too long, especially for wireless communication.

The mechanism of how many maximum bytes are contained in each frame is called fragmentation. Most of the time, we are not allowed to adjust it on RF devices for several reasons. If the MTU is set too small, we will have lots of overheads in communication, interframe spacing and ACKs, which are definitely inefficient to usage of bandwidth and which are harmful to throughput, since atomic procedure in wireless is a three-way handshake. On the other side, setting a very big MTU seems to overcome these problems previously mentioned; however, it is worse than setting a small fragmentation in most cases. Firstly, even though each device in a wireless communication domain still has a fair right to content for the medium, it may occupy too long a time for sending frames in big sizes, as other STAs have to wait throughout the period. Secondly, attenuation and corruption of packet data will require the retransmission of long bit frames rather than just parts of them.

Therefore, such a setting also drastically reduces wireless throughput and ultimately wastes bandwidth. Just like most designing tasks, it is important to find a tradeoff between MTU and overheads for certain wireless communication environments, rather than having an absolute solution that is good for all cases.

5.4 Summary

In this chapter, we reviewed a higher MAC layer protocol (IEEE 1609.4) for the multi-channel operation of DSRC, which is based on CCH and SCH further adopting WSM and IPv6, respectively, at higher layers of transmission. Such a mechanism brings STAs in VANET form either a unique WBSS or non-WBSS topology on different channel intervals. Meanwhile, formats of WSM and WSA, which are exclusively for the CCH broadcast mode, have been carefully studied.

Chapter 6 Simulation Elements Configuration and Fundamental Scenarios

The OPNET Modeler Wireless Suite provides high fidelity modeling, simulation, and analysis of a broad range of wireless networks. Given that OPNET is the de facto standard for wireless network simulation, we decided to use OPNET. However since OPNET does not have IEEE 802.11p modeling yet, we had to modify the current 802.11a protocol for our study.

6.1 Introduction of 802.11p Simulation

All simulations conducted for the 802.11p performance study on following chapters will base on OPNET 14.0 with wireless suite, which is a comprehensive analyzing tool for both wired and wireless networks. Since the unique characteristics of 802.11p standards distinguish themselves from other WLAN standards, many aspects, including but not limited to operating frequency, bandwidth, broadcasting nature on CCH, QoS mechanism that is based on EDCA, and road traffic situations, will have to be considered. One of the most important things, which is needed to be noticed, is that we should not take 802.11p simulation as a bunch of laptops equipped with 802.11a in movement. Instead, it should be considered an absolutely different wireless standard exclusively for vehicular application.

By virtue of OPNET, most characteristics of 802.11p can be carried out in order to facilitate relevant researches in this thesis. However, it is necessary to mention that the simulation would not be able to cover every aspect of 802.11p but rather prove our best efforts to approach it, due to two facts briefly stated as follows:

Firstly, 802.11p has just been finalised in July this year. Thus, there is no immediate module able to be adopted from OPNET. As 802.11p is a modified standard of 802.11a, the simulation inevitably relies on the amendment of its PHY and MAC parameters. Meanwhile, even though OPNET is very professional software for wireless network research, its limitation in functionalities makes it difficult to fulfil all mechanisms of 802.11p application. For instance, there is no frequency switch function between CCH and SCH. Furthermore, OPNET does not allow the deployment of multiple access categories on a single WLAN workstation.

Secondly, as 802.11p will be applied to dynamically changing environments as well as the main objective of this thesis being to focus on the analysis of performance based on its PHY and MAC mechanisms, some factors, such as propagation model, terrain, and road traffic situations, have to be chosen either ideally or empirically. Otherwise, the simulation results will be affected by too many random factors and will handicap the general analysis.

Despite the disadvantages mentioned above, these are actually the very factors bringing challenges and interests to the 802.11p simulation performance study, as most difficulties and software limitations could be overcome by alternative ways.

The simulations and analyses in this thesis mainly focus on CCH performance of 802.11p, as it is the most important and critical part of VANET application, which can be further divided into several subsections in order to study the impacts, such as distance, packet size and vehicle traffic flow on VANET individually. Finally, a comprehensive performance under a dynamic environment will be studied.

6.2 Workstation Configuration and Explanation

The OPNET configuration for the node workstation is the key part of our simulation, which contains necessary parameters for further topology deployment. Each main parameter is explained as follows:

1. Min Frequency: Concerning CCH simulation, all vehicles should work at a central frequency numbered 178 and should be between 5885 -5895 MHz. Therefore, Min frequency should be 5885 MHz.
2. Bandwidth: All simulations choose 10 MHz, as standardised, and disregard the 20 MHz situation.
3. Physical Characteristics: 802.11p is a modification of 802.11a, which is the only approximate choice in OPNET and which expects to bring the closest performance.

4. Data Rate: The data type of Data Rate in OPNET is double. As 3/6/12 Mbps are three mandatory rates in 802.11p standards as well as the first two rates being adopted under poor wireless communication, 6 Mbps will be used for CCH simulation, which is a reasonable and popular choice for most IEEE papers related to 802.11p.
5. Transmission Power: We know that 802.11p is supposed to provide communication within one kilometre, which will be adopted in simulations. Meanwhile, as OPNET does not provide a power self-adjustment function, it is necessary to calculate precise transmission power as a very important parameter, not only according to data rate but also as the internal mechanism of OPNET. After reviewing and reading different research papers, they show that different transmission power settings have been used, such as 20, 40, or even 3 dBm, which cannot all be applied to my simulation directly. A brief introduction of transmission power estimation is stated as an Appendix and the result showing 0.01939555 W (12.877 dBm) is needed.
6. EDCA Configuration: Throughout our simulation, there are four kinds of access categories (ACs) that will be applied, namely Background (AC 0), Best Effort (AC 1), Interactive Voice (AC 2) and Reserved (AC 3), whose related AIFSN and CW will be set according to Table 4-2, which is listed in Chapter 4. Figure 6-1 gives an example of PHY and EDCA settings for AC 3 setting.

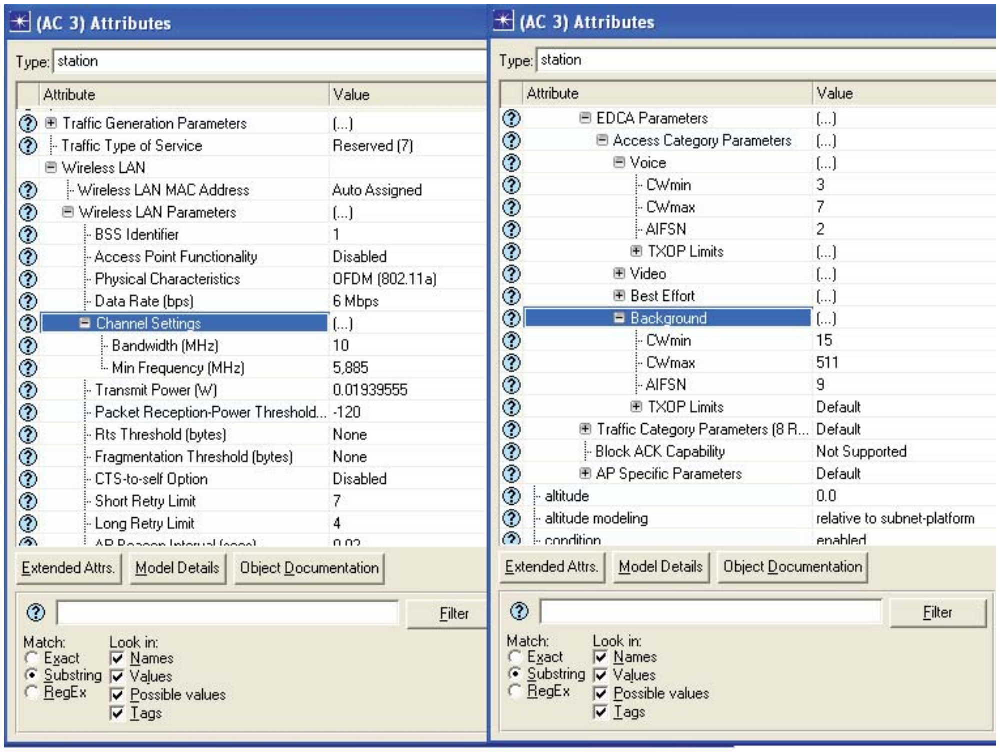

Figure 6-1 PHY and EDCA Configuration for AC 3

There is one thing which needs to be explained here. Due to the OPNET limitation mentioned previously, namely there being only one AC for each workstation, the consideration of an OPNET workstation equal to a vehicle should vary with real applications, whereby one vehicle might temporally broadcast one or more AC on its CCH. In the former case, they will be equal to each other; however, things will be relatively complex when more than one AC exists in one vehicle. An immediate thought might be to combine multiple workstations to represent one vehicle. As such, an alternative solution has been widely used in other research papers, for EDCA performance studies and also in this thesis. However, some clarification and analysis need to be provided before we adopt it.

1. It will not always be equal to the vehicle, when sending multiple ACs. At first glance, these ACs seem like content media simultaneously and would be the same if more workstations were added to represent them. Indeed, they are equal when there is no collision happening in VANET. However, in case of collision, whose types, namely internal or external, differ depending on whether two collided signals come from

workstations belonging to the same vehicle or not, there are a further two sub-cases under which external collision still maintains the equalisation for an alternative solution. However, in case of internal collision, the EDCA standard requires a packet from comparatively low priority AC to perform exponential backoff, which cannot be carried out by OPNET due to two reasons: firstly, despite being called internal collision, it actually happens in external collision form in OPNET, as the collided signals come from different workstations and are taken as "Noise/Interference" at the receiver end. On the other hand, due to the lack of CTS/RTS mechanisms under the broadcast mode, a collision will not be detected by transmitter and no corresponding backoff will be made.

2. An alternative solution will bring a sort of statistical inaccuracy but will be acceptable. As we mentioned previously, in case of internal collision, the AC with higher priority will be sent first, which means that, in real practice, AC 3 will never suffer from collision backoff under the CCH broadcast mode. By reviewing OPNET simulation, we can see that the same situation happens and, in fact, AC 3 might perform worse in comparison to the real situation. For instance, imagining there are AC 3 and AC 2 with lower priority, which are all sending packets numbered P-0, if a collision happens, P-0 of AC 3 will send, and its AC 2 counterpart will not only wait 3 time slots but will also choose a contention window from [0 7] rather than [0 3] (i.e. higher probability of waiting longer to gain media access). Since OPNET does not provide broadcast backoff functionality, in this case, both P-0 of AC 3 and 2 will disappear and P-1 of AC 3 will try to compete with its counterpart of AC 2, which still uses an initial CW range [0 3]. Figure 6-2 illustrates this example.

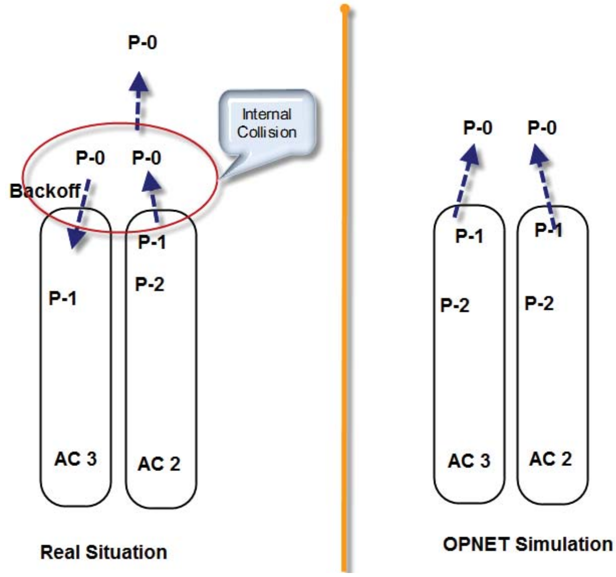

Figure 6-2 Contention and Backoff Mechanisms in Two Situations

Therefore, in OPNET, we actually would get a higher delay and lower throughput for AC 3, which underestimates real situation performance. On the other hand, the performance of lower ACs might be overestimated. The reason we say it is acceptable is due to our simulation focus being on the study of AC 3 performance in a relatively nasty environment, whose feasibility will not be affected by underestimation as long as it meets pre-defined criteria.

3. Since there is no exponential backoff mechanism under CCH simulation, inter-AC collision should theoretically never happen on some pairs under an ideal propagation mode and saturated network as long as

$$(CW_{min} + AIFSN)_{higher\ priority\ AC} < AIFSN_{lower\ priority\ AC}$$

Therefore, these non-collision groups can be summarised as follows:

[AC 3, AC 1]; [AC 3, AC 0]; [AC 2, AC 0]; Meanwhile, [AC 2, AC 1] have a very slight possibility of having a collision unless value 0 is chosen for CW of AC 1.

What is stated above provides a fundamental conception and justification of our simulation. Meanwhile, each of our simulation scenarios focus on the impact of different aspects on VANET performance, whose relevant deployment and theoretical foundations will be given in more detail in the following sections.

6.3 A Simple Simulation Scenario

6.3.1 Deployment and Performance of Scenario -1

In order to review the general performance of the EDCA mechanism, we firstly deployed a relatively simple scenario-1, where three vehicles exist and each contains four ACs. Logical subnets (vehicles) will be used for the purpose of eliminating any dimension impact. Meanwhile, a testing node for the performance study is necessary, which does not involve any media contention. The reason we adopt this node is because node sending AC in OPNET can only collect delay statistics from other nodes but not itself. Figure 6-3 illustrates the topology of scenario-1.

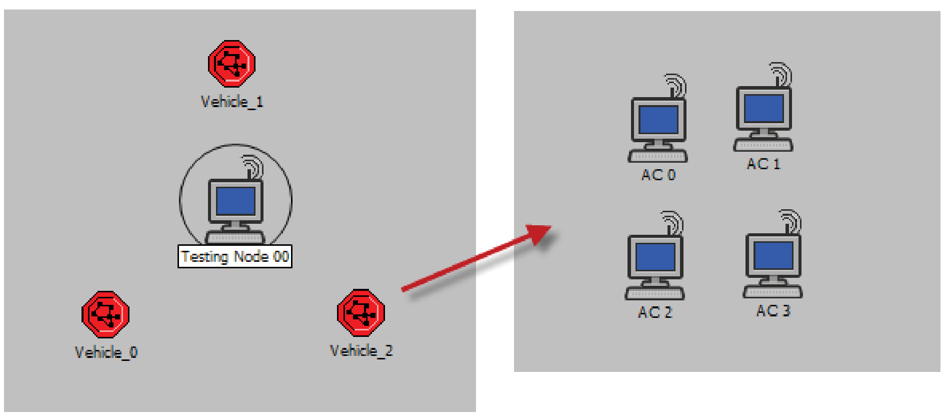

Figure 6-3 Topology of Scenario-1

Next, we need to define packet generation parameters for each AC, which is actually the most difficult part of CCH simulation for two reasons. Firstly, 802.11p is a new standard, whose applications based on upper layers has not been widely studied. Therefore, it is difficult to define a real range for packet size at current stage. In [57], we know that WSM should not exceed 1400 bytes and that its header size ranges from 7 to 16 bytes if the extension field is included. On the other hand, the packet generation interval (heartbeat rate) and packet size for each AC differ from each other in research papers, as 802.11p operates in a dynamic environment and each paper has a specific focusing area. Therefore, the parameters for packet generation in this thesis may vary and may be adjusted based on empirical and theoretical data; meanwhile, they will be reasonable and appropriate.

By combining data adopted by [58] and [59], modified parameters in this thesis for different AC are listed in Table 6-1 and may be further adjusted.

Table 6-1 Packet Generation Parameter

Access category	Packet Generation Interval	Packet Size	Transmission Rate (bps)	Annotation
AC 3	0.1	29	290	WSM example from [56]
AC 2	0.1	80	800	
AC 1	0.1	512	5120	
AC 0	0.1	207	2070	WSA example from [56]

The above-listed packet generation parameters, together with EDCA for CCH, are the two main factors throughout simulations. Within the four ACs, AC 3 and AC 0 represent WSM and WSA, respectively; however, only the former will gain the highest attention and the rest of the ACs can either generate lower traffic streams or even be sacrificed in order to maintain the performance requirement for safety-related communication. Moreover, the heartbeat rate is chosen at 10 Hz (equal to 10 packets per second), which is not only practical but also reasonable, as the sync interval is 100ms by default and the message broadcasting in real situations would be very discrete (i.e. it is not possible to have more than 10 safety-related warnings within just one second). Some papers might use a 100 Hz packet generation frequency, which seems a bit overestimated. Whilst considering a 2m guard interval for channel synchronisation, we further set "Start Time (seconds)" to be mean outcome 2ms in exponential distribution and extremely small values of 'OFF State Time". Figure 6-4 illustrates the configuration for AC 3 packet generation.

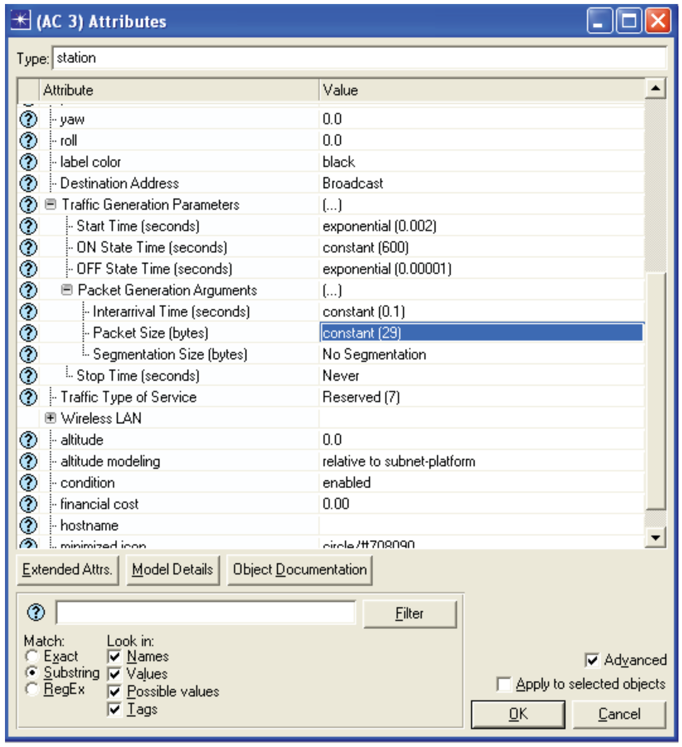

Figure 6-4 OPNET Setting for AC 3 Packet Generation

We ran this simulation in OPNET for 10 minutes. Meanwhile, since a 10 Hz packet generation interval is very discrete to OPNET, we therefore set "Values per statistic" to be 10000 in order to obtain better statistical observation. The delay of each AC for this simulation is given in Figure 6-5 under overlaid presentation.

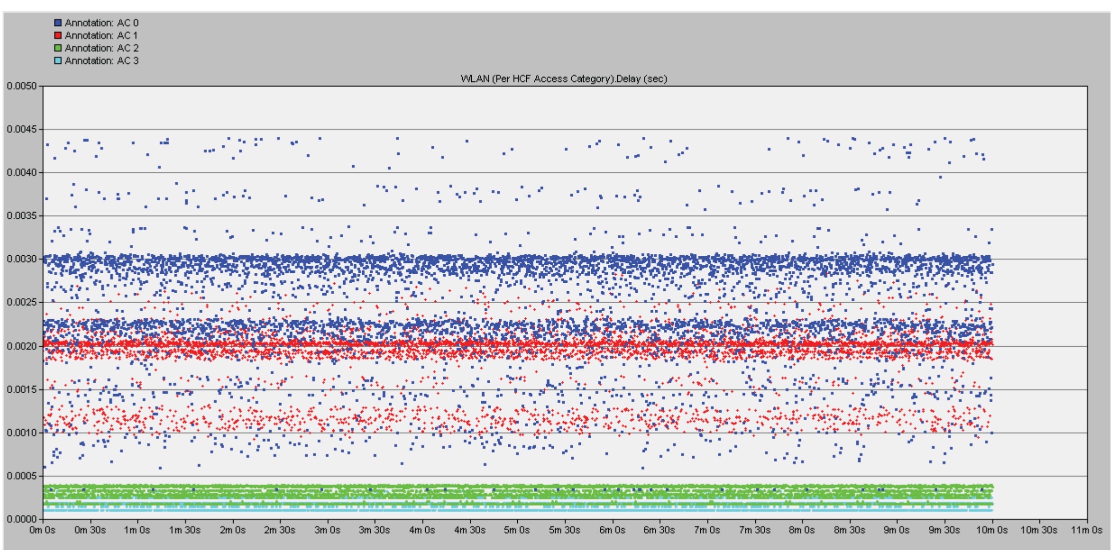

Figure 6-5 Delay of ACs in Scenario-1

6.3.2 Performance Analysis

Analysis: Since 802.11p is not supposed to provide a regular internet access purpose, we mainly focus on the performance of delay. Through reviewing the above results, no fixed delay parameter could be obtained. However, its range and all statistic points scattered with different scales, although each AC densely locates at a certain band, which is expected to be the average delay value for them. In order to facilitate our analysis, this data has been exported to a spreadsheet in Table 6-2 and the average delay is shown in Figure 6-6 below:

Table 6-2 Data for Delay of Each AC

Access category	Max Delay in ms	Average Delay	Max/Avg. Ratio
AC 3	0.323	0.1742	0.539318885
AC 2	0.395	0.3089	0.782025316
AC 1	2.838	1.87	0.658914729
AC 0	4.401	2.52	0.572597137

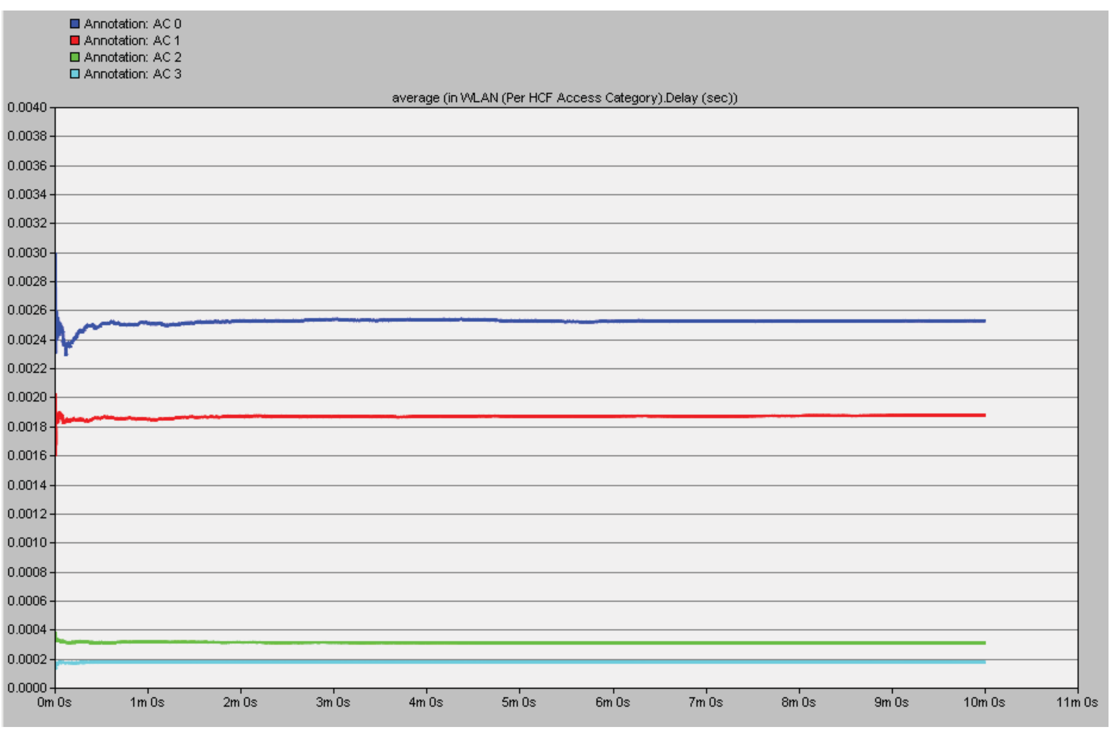

Figure 6-6 Average Delay of ACs in Scenario-1

By reviewing the diagram, we can see that EDCA is quite a robust MAC mechanism, in terms of it maintaining priority as the layout of delay for each AC. In particular, even the packet size of AC 1 is doubled, compared to that of AC 0; its average delay is still smaller than AC 0. On the other hand, AC 3 not only suffers the lowest delay but also the most stable one, compared with its counterparts, as its Max/Avg. Ratio is only 53.9%, which is similar to the 57.2% of AC 0. Meanwhile, AC 2 and AC 1 had approximately 78% and 65.8%, respectively. It can be concluded that within four ACs, the ones with either the highest or lowest priority will experience a smaller delay fluctuation than others. Furthermore, it looks like these four ACs can be mainly divided into two major groups, namely AC3/2 and AC 1/0, whose delay gaps are remarkably noticeable on the above diagram. However, at this moment, we cannot analyse the delay difference between members of the same group, as different packet sizes have been deployed in ACs; although, we predict that AC3/2 should always have a smaller internal delay difference than AC1/0, which will be proved in the following subsection of this thesis.

6.4 Study of Distance Impact on CCH Performance

6.4.1 Deployment of Stationary Scenario-2 and Performance

Previous simulations could actually only prove that EDCA works and that priority for each AC is apparent. However, the average delay for each AC obtained was under an ideal situation and could therefore not be adopted directly, since, in practice, whether or not communication distance and vehicle velocity will impact 802.11p performance needs to be further examined.

For this purpose, we created scenario-2, which is based on the previous one, by deploying a 5x1 km map in which the logical subnet containing three vehicles is located at 500,500 m. One (numbered as 00) of eight testing nodes is placed in the logical subnet and the rest are each spaced at 200m. Figure 6-7 shows the topology of scenario-2.

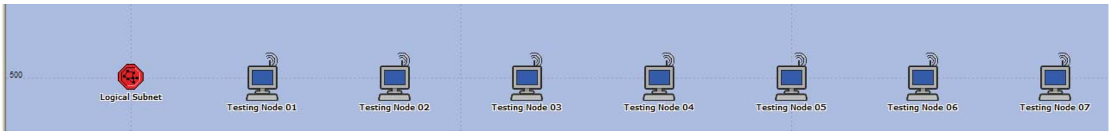

Figure 6-7 Topology of Scenario-2 for Distance Impact Study

As previous designed, the transmission power in our simulation covers 1 Km effective distance judging by throughput. Testing Node 06/07 will be out of the 1 Km range and will therefore be used for further study. It is assumed that the distance will affect almost every aspect of wireless communication, including delay, throughput, bit error rate (BER), signal-to-noise ratio (SNR), etc. Various performances of AC 3 for different testing nodes are given by Figure 6-8~13.

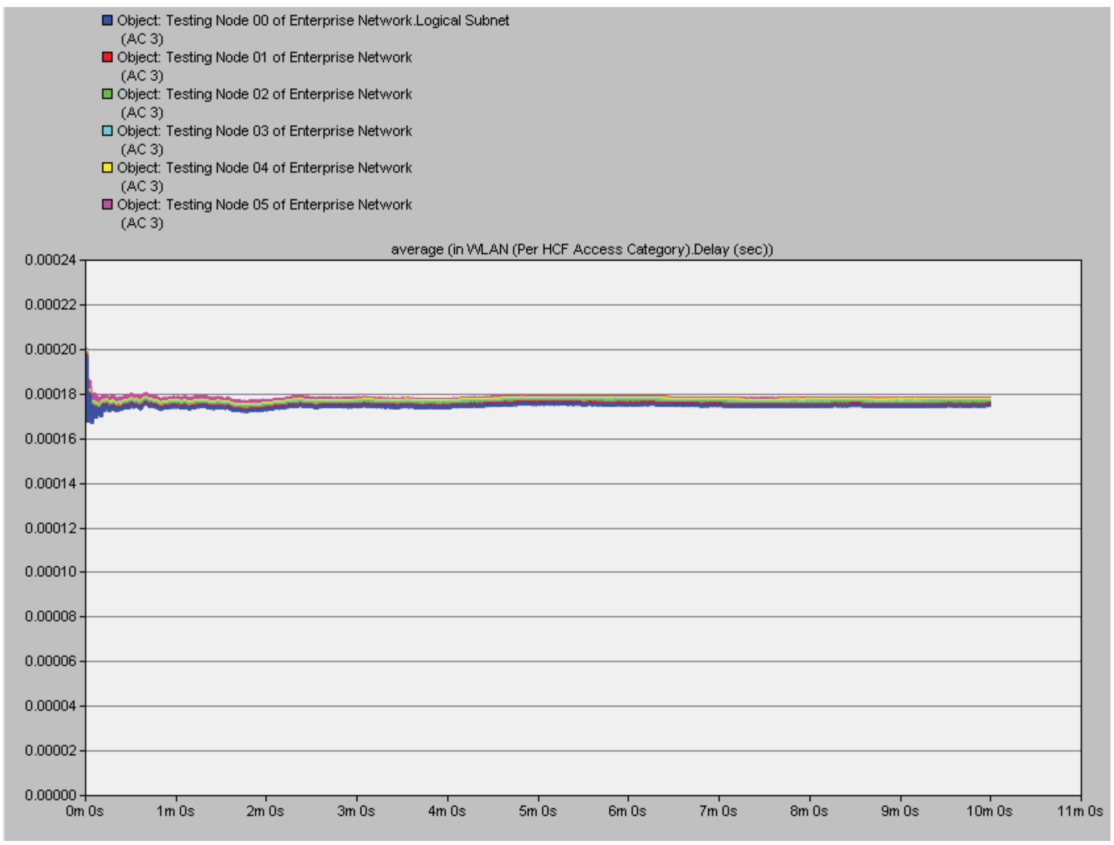

Figure 6-8 AC 3 Average Delay for Testing Nodes 00-05

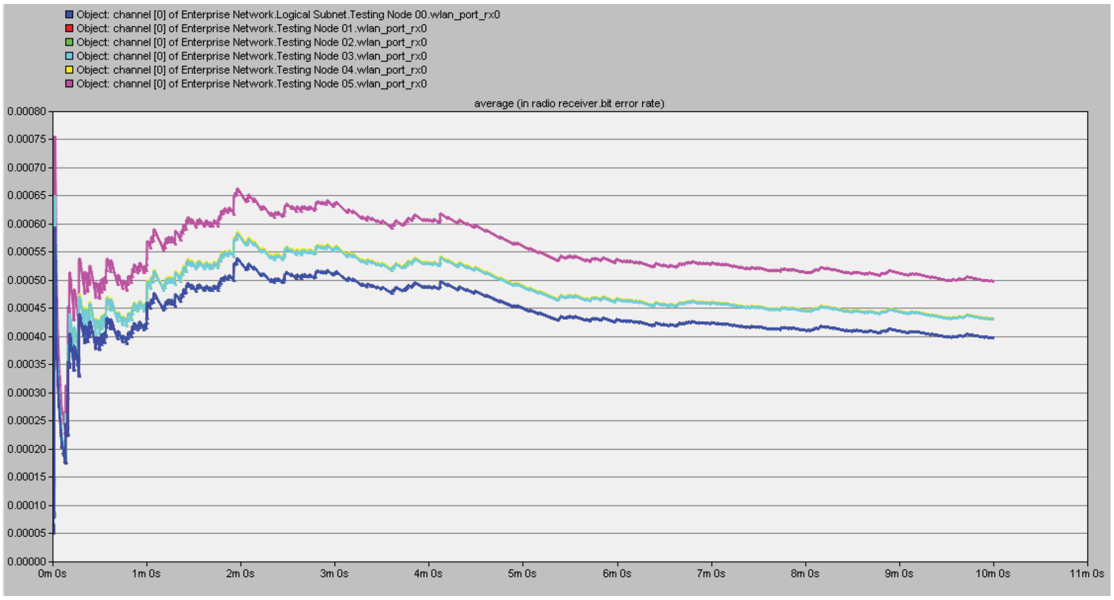

Figure 6-9 AC 3 Bit Error Rate for Testing Nodes 00-05

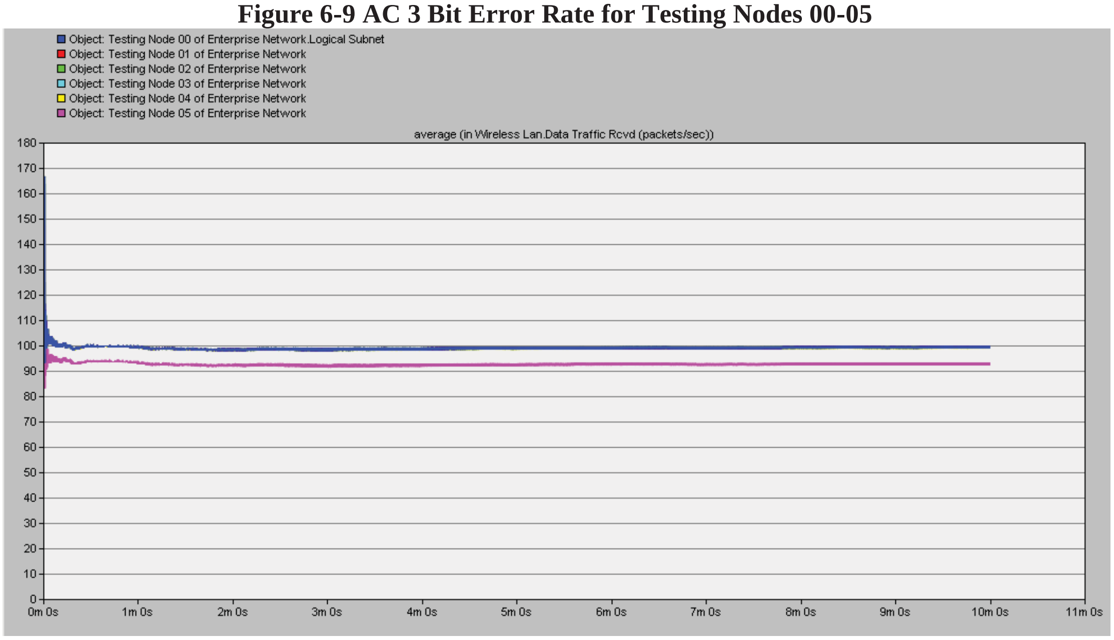

Figure 6-10 AC 3 Packet Receiving Rate for Testing Nodes 00-05

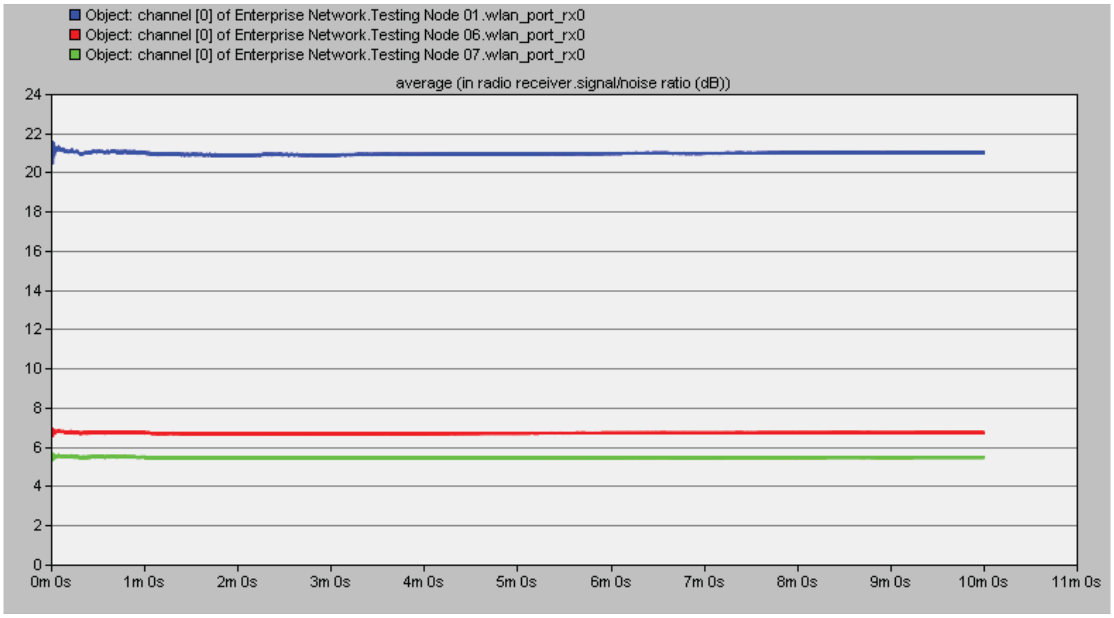

Figure 6-11 SNR of Node 01/06/07 in Scenario-2

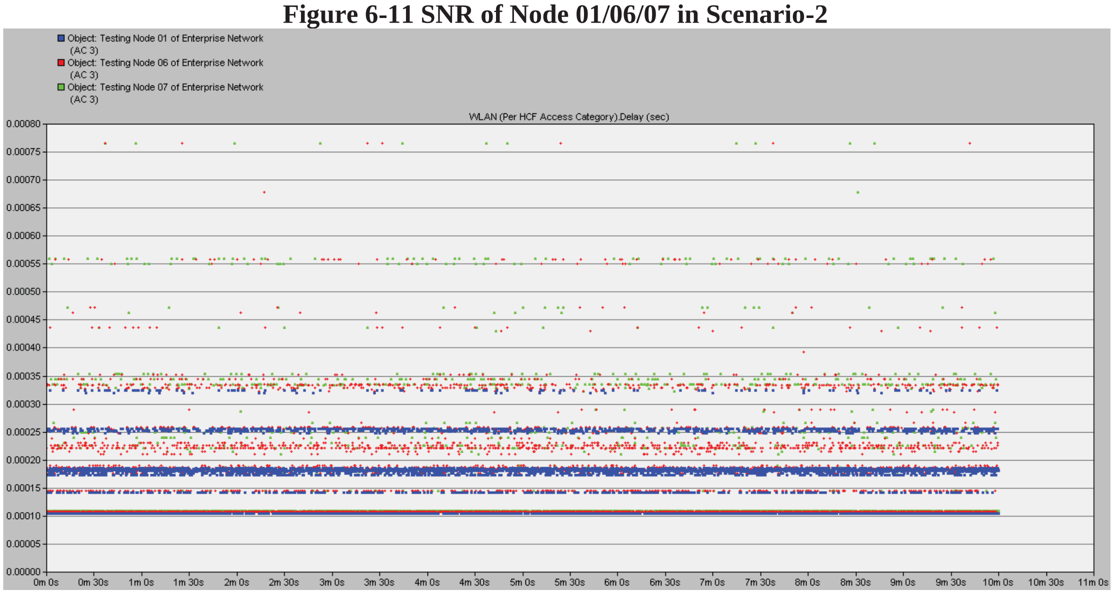

Figure 6-12 AC 3 Delay of Node 01/06/07 on Scenario-2

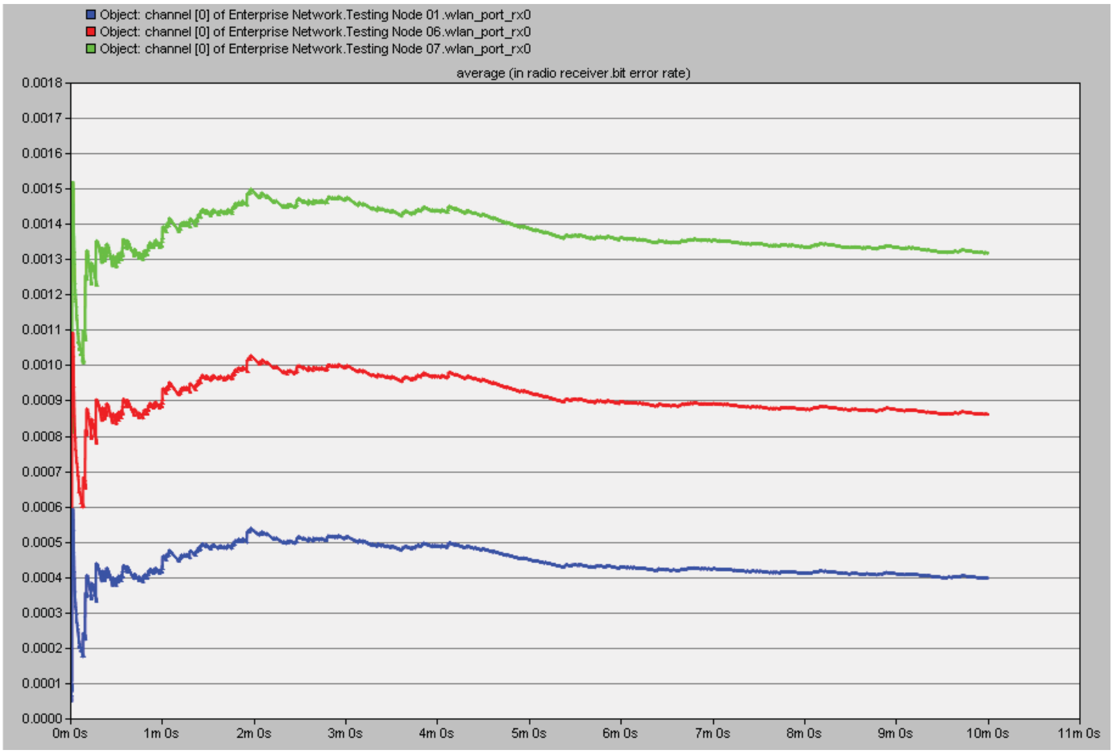

Figure 6-13 Average BER of AC 01/06/07 on Scenario-2

6.4.2 Performance Analysis of Scenario-2

6.4.2.1 Analysis within Effective Coverage

Analysis: Since the distance impact to communication performance is pretty complex, merely judging from the average delay of each node will not be enough. Instead, we observe three indicators for our performance study, namely average delay, BER and packet receiving rate. Firstly, we can see that, within a 1Km distance, all nodes have almost the same average delay and are slightly increased according to distance from data source. This can be explained by an increased BER, which is acceptably given in Figure 6-9, due to a relatively greater attenuation by distance. Since the delay is a compositive performance, including hardware efficiency, propagation, processing, etc., in this case, we can consider the slight increase in node 05 delay being down to more processing time taken by correcting received bits as well as propagation delay. Furthermore, we know that the relationship between SNR and BER under QPSK from [60] is as follows:

$BER=\frac{1}{2}\ \mathrm{erfc}\sqrt{\frac{E_b}{N_0}}$ (Equation 6-1)

$SNR=\frac{E_b}{N_0}\frac{R_s}{B}$ (Equation 6-2)

Where $\frac{E_b}{N_0}$ is carrier-to-noise ratio, R_s and B represent data rate and bandwidth, respectively.

The two equations above actually indicate that the BER will be dynamically affected by SNR according to distance change (i.e. lower SNR results in higher BER). In real application, with the purpose of extending coverage, vehicles should switch to a lower data rate (i.e. a simpler modulation mechanism to obtain a lower sensitivity requirement or to intelligently increase its transmission power, together with more advanced hardware components, such as an equalizer, in order to cope with multipath propagation and a fading phenomenon).

Meanwhile, there is an abrupt packet receiving rate drop at Node 05, from 98.92 packets/s to 92.45 packets/s, due to an edge effect related to a sensitivity issue, which will be explained in detail later on.

6.4.2.2 Analysis Outside of Effective Coverage

Next, we observe the performance of testing nodes 06 and 07, in contrast with 01, based on their SNR, delay and bit error rates from Figure 6-(11~13). It can be observed from Figure 6-12 that the longer distance has the larger swing range of delay and thus more scarce sampling nodes on the diagram. Through comparing the BER between nodes 06 /07 and 00, they increased almost by 213% and 100% on average. What we need to focus on is the peak AC 3 delay for each testing node, rather than their average values, as we found that the peak delay for node 00 is around 0.323 ms, compared with 0.766 ms for node 07, which can be explained by the same reason for a processing delay (mentioned above). Although the delay has increased by 137% outside of coverage, under VANET with only three vehicles, it might seem acceptable. However, on the other side, the scarcity observed actually impacts on the performance at the highest level and is the very reason for causing the effective pre-design coverage. Firstly, we know that CCH always works on the broadcast model and that there is no retransmission sent differently from normal WLAN applications, in which a user will experience extremely slow throughput and frequent disconnection, but can still feel “useful”. A typical case might be that your wireless adapter detects weak Wi-Fi signals without encryption leaking from your neighbour’s house; you can take advantage of slowly opening some web pages rather than watching YouTube smoothly. However, in traffic safety application, almost all messages on CCH are expected to be received without exemption and there is no selective or occasional receiving that is tolerated. Secondly, the cause of lower receiving rates is mainly the sensitivities of receivers; the turning point in communication performance is varying the different modulation schemes. According to Equitation 7-2, the SNR will increase under a higher data rate. Most of the time, the receiving status will abruptly deteriorate when the signal strength is below the sensitivity, thus causing a great amount of data which cannot ultimately be decoded and dropped. Here, we need to distinguish the difference between receiver sensitivity and the packet reception-power threshold. The hard figure of the former is provided by a few manufacturers but is a measure of the minimum threshold at which a device can properly detect and interpret a signal, which implies two facts: firstly, under this threshold, a device is still allowed and might be able to detect signals. On the other hand, even though it can detect the signal, the interpretation will perform improperly without any guarantee. The latter (reception-power threshold), however, is a very precise value under which a signal will not be sensed nor decoded. Therefore, by setting this parameter with a smaller value, we can see that the signal is being ‘cut off” immediately without any exemption, even if it can still be properly decoded by a receiver. Since the sensitivity is merely hardware-related and cannot be changed, the power threshold actually has a great meaning to vehicle communication under the two scenarios stated below:

1. If the data source would like to confine the transmission range within certain coverage or eliminate receivers under a poor communication environment, it can define the fixed value of the power threshold in its packet header rather than just merely increasing its transmission power. This is based on several reasons: firstly, not all vehicles have to receive data, especially in the SCH case. Secondly, since VANET

operates in a highly dynamic environment, merely changing the transmission power would not always help to better the performance but rather increase interference. Furthermore, by informing receivers of the threshold, we actually handle the rights of decisions of acceptance rather than forcing the communication.

2. As we know, under the broadcast mode, CSMA/CA will still be involved in media access contention, which contributes to most of the delay. Generally speaking, how long a certain node needs to wait in order to gain access to the media is dependent on the number of nodes within the effective communication coverage. At the edges of broadcast distances or even further, even though the signal strength is much lower than sensitivity, nodes there might be content with redundant counterparts, which are not supposed to be taken into consideration. For instance, based on common sense, we know that the pre-crash messages are generally only meaningful to the vehicles behind the sending source; this is in order to let drivers brake as soon as possible. However, since mainly isotropic antenna will be adopted in VANET, these messages will inevitably send to the vehicle not only in front but also outside of pre-defined coverage and will thus make receivers try to sense them. Therefore, if vehicles are able to set a reception threshold according to distance and dynamic environment, their performance will not be affected by vehicles outside of their coverage and will look better due to the receivers ignoring signals below their threshold. In fact, in a long queue of vehicles in a traffic congestion period, most vehicles can be considered at the edge of certain effective communication coverage. Thus, this parameter will improve the overall network performance rather than several members of it.

6.4.3 Deployment of Dynamic Scenario-3 and Performance

Furthermore, in order to demonstrate the analysis stated above and to obtain the dynamic distance impact to network performance, we set another testing node (08), which is moving at a low velocity of 1 Km/h, in order to eliminate the Doppler effect from 500,500 to 2500,500. Topology for this mobile scenario-3 is given in Figure 6-14.

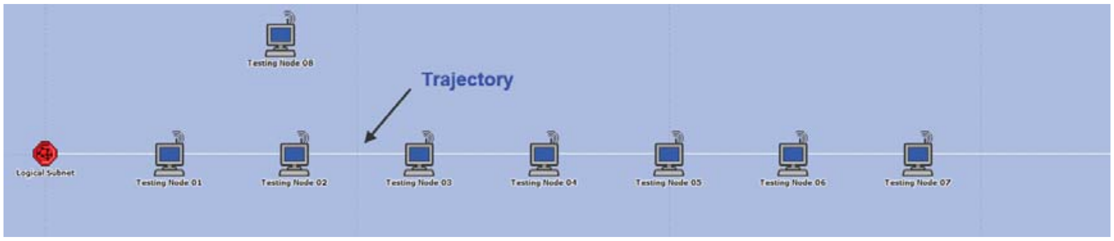

Figure 6-14 Topology for Scenario-3

After running this simulation, related performances are given below:

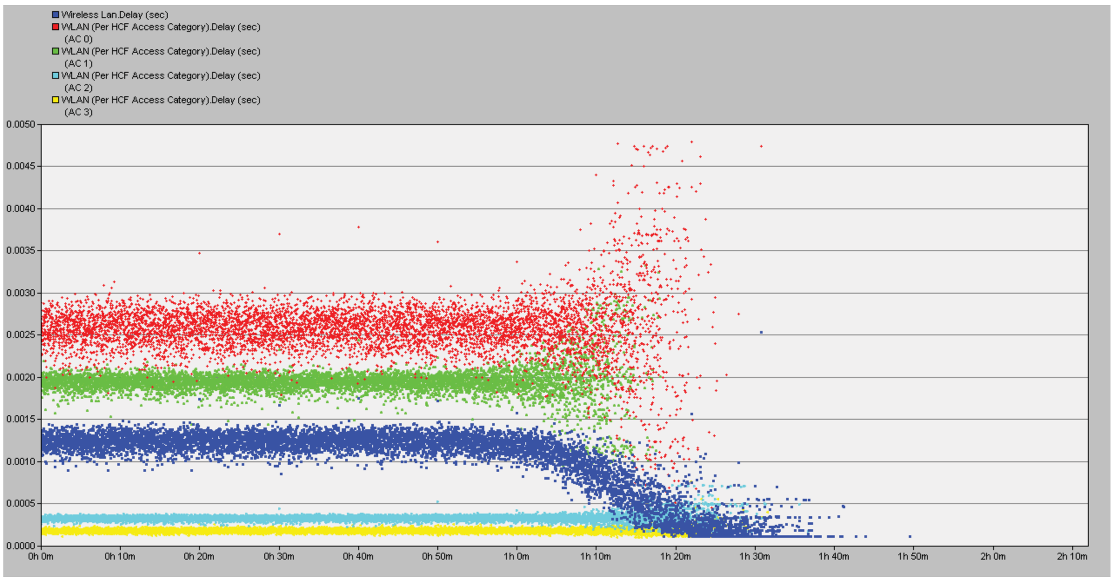

Figure 6-15 Overall Delay and Delay of ACs in Discrete Pattern

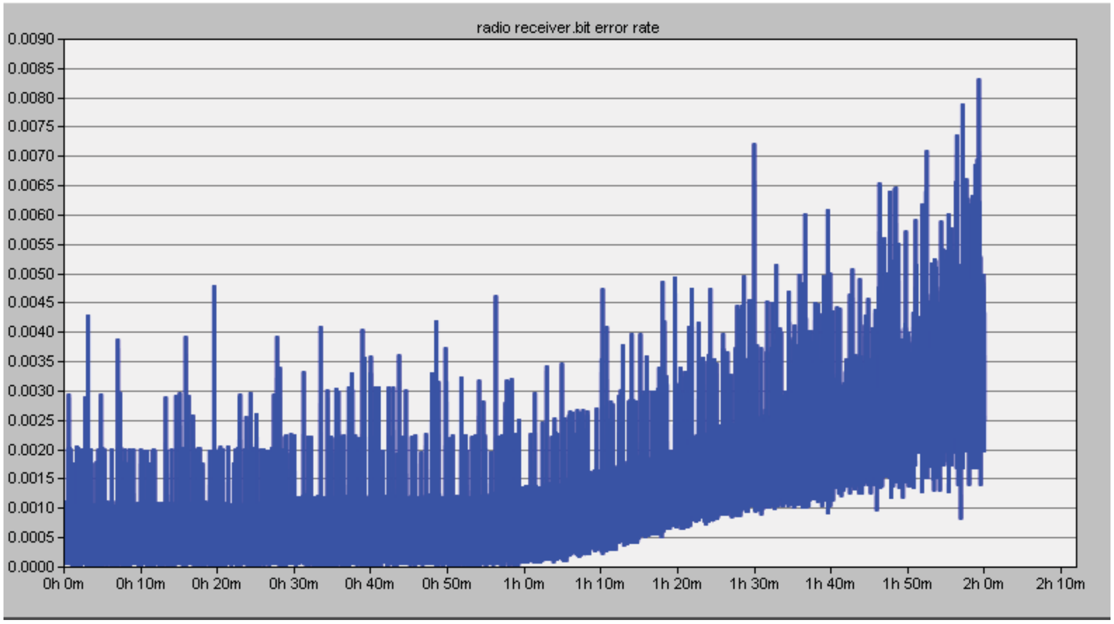

Figure 6-16 BER of Node 08

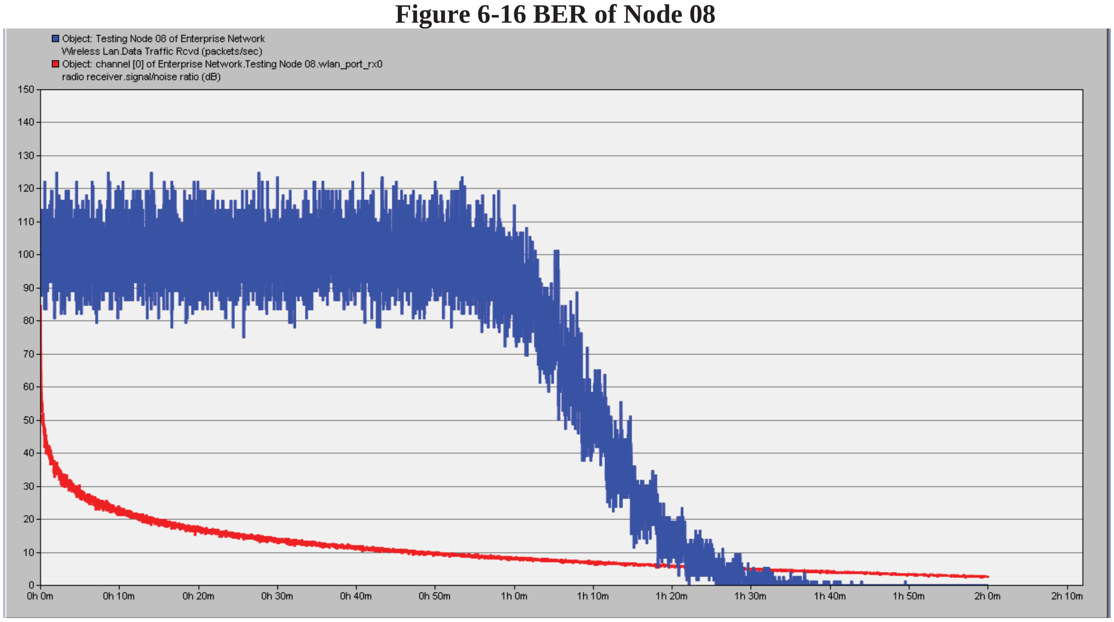

Figure 6-17 Packet Reception Rate and SNR in dB

6.4.3 Performance Analysis of Scenario-3

Analysis: It is not surprising to find that within a 1 hour duration that is equal to the 1 Km distance, the whole network provides a stable performance in which there is no noticeable change of delay and packet reception rate, and the BER only slightly increases. On the other hand, the related performance abruptly deteriorates when out of coverage, due to sensitivity issues mentioned previously and the SNR below being around 10 dB.

What drew our attention turned out to be the gradually reduced overall delay, which combined all four ACs. However, as mentioned previously, according to distance and BER increase, the delay should slightly increase. Such a phenomenon can be explained by the reserve proportional relationship between packet size and reception distance; as can be observed from Figure 6- 15, AC 2 with the highest packet size of 512 bites can only be received at the shortest duration due to two reasons stated below:

1. Under the same modulation scheme, a packet containing more bits requires more OFDM symbols to be transmitted. For instance, the PHY layer of 802.11p at 6 Mbps adopts QPSK, whereby data bits per OFDM symbol is 48. When signal strength is below the sensitivity, one or several OFDM symbols belonging to certain packets could neither be sensed nor decoded, thus making an incomplete packet reception that is dropped by the PHY layer. Therefore, a packet with a bigger size will generally experience an extremely higher symbol loss probability. This can be proved if we confine the packet size within one OFDM symbol by resetting the size of AC 3 to 10 bits and AC 2 to 20 bits. In this case, the PHY layer of transmitter will pad the remaining bits for this packet in order to consistently place it into a complete OFDM symbol. Figure 6-18 shows the results.

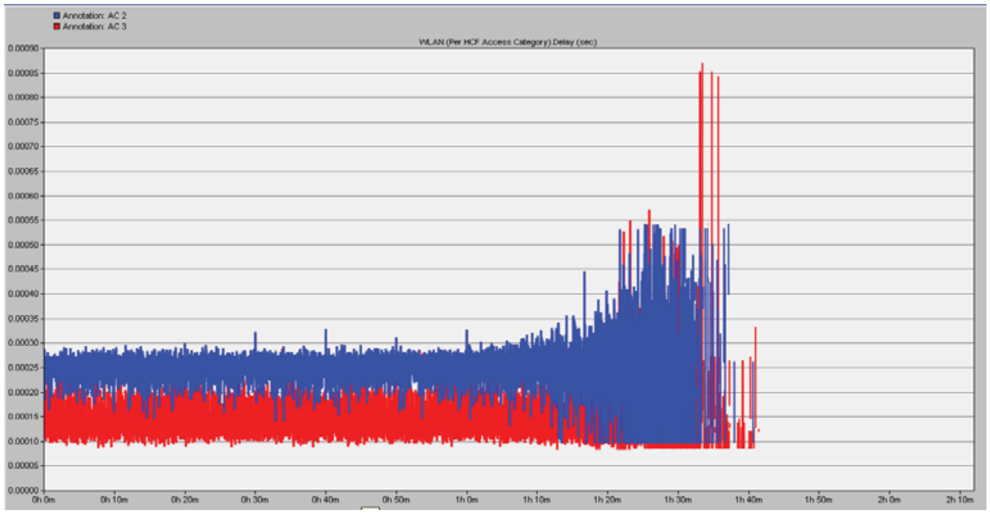

Figure 6-18 Reception Distance Under One OFDM Symbol

From the above diagram, we can see that AC 3 and AC 2 can be received almost at the same distance, which proves our previous assumption.

2. Furthermore, the packet error rate (PER) p_p will not evenly allocate on different ACs with various packet sizes, according to [61]

   $p_p=1-(1-p_e)^N$ (Equation 6-3)

   p_e is the bit error rate.

   The above equation indicates that the PER has an exponential relationship with packet size. Therefore, AC 1 with 512 will experience an extremely high PER reaching 100% very quickly when out of coverage. One thing needed to be mentioned here is that the observed BER from OPNET cannot be used to calculate p_p directly, since it has been defined on OPNET as BER for bits of the packet, which is completing arrival at the receiver channel, and the real BER is actually much higher than that. The continued increasing PER, which is due to abruptly deteriorated BER, when outside of coverage causes packets to be dropped by PHY, as we can see from Figure 6-17.

   The reasons given above explain why the overall delay decreases rather than increases; as with the four ACs, packets containing relatively high bits and a lower priority will first experience dropping, which further makes AC 3 become the dominant one at the receiver end, according to distance increase.

6.5 Study of Packet Size Impact on VANET

6.5.1 Introduction and Deployment of Scenario-4

This subsection is the key part of this thesis and the most important component of our simulation, as the impacts of packet size and vehicle number on VANET are pretty complex, which, in most cases, cooperate with each other in order to dominate network performance. At first glance, it is obvious that the increase of either packet size or vehicle number will lower the performance, namely a longer delay, higher interference, etc. Moreover, increasing a packet size is somewhat similar to increasing vehicle number but they will never be equal, just like the time spent picking up a bag of wheat being tremendously different from picking up thousands of grains of wheat, despite being at the same weight. Thus, the delay of two nodes sending 1000 bits/packet will be different from four nodes sending 500 bits/packet.

Due to the complexity mentioned above, we will first study the packet size impact on VANET independently, which is a 2D pattern. After that, the factor of the number of vehicles will be added into our study and will finally form a 3D pattern, namely packet size, vehicle number and performance. Since each vehicle might carry one or more ACs, the study of the relationship between packet size and performance itself requires a lot of work. After careful consideration, three instances will be examined in this subsection, which are based on three vehicles of topology; a brief introduction is given as follows:

1. Only one kind of AC exists in VANET. This is used to study packet size impact on individual ACs.
2. Based on 1, we added another three ACs into VANET, which helps to study the MAC contention mechanism's impact on certain kinds of AC.
3. Based on 2, we checked the performance of the added three ACs in order to study how one kind of AC impacts on the whole system performance.

Scenario-4 was created in which there are four subnets numbered from 00 to 04, which are spacing at least 1Km each. Each of them is used to study a certain AC containing three vehicles and one testing node, whose category is the same as the subnet number. For instance, subnet02 only focuses on the performance study of AC 2 and subnet04 is reserved for future usage. Also, the packet reception power threshold is reset to -80 dB in order to eliminate possible interference. Figure 6-19 illustrates the topology of scenario-4.

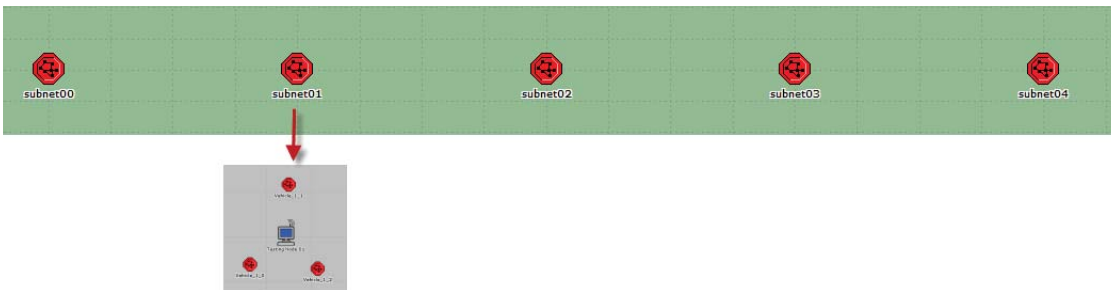

Figure 6-19 Topology of Scenario-4

6.5.2 Analysis of Instance-1

We deploy the same kind of AC in each subnet and turn off the other three ACs. Then, the packet size for each workstation will be increased to the power of 2 based on 48 bits till 768 bits, together with a special instance of 1400 bits as the maximum allowed size for CCH. After running the simulation eight times, the diagram for the average delay of each AC is given in Figure 6-20. Detailed data can be found in the Appendix.

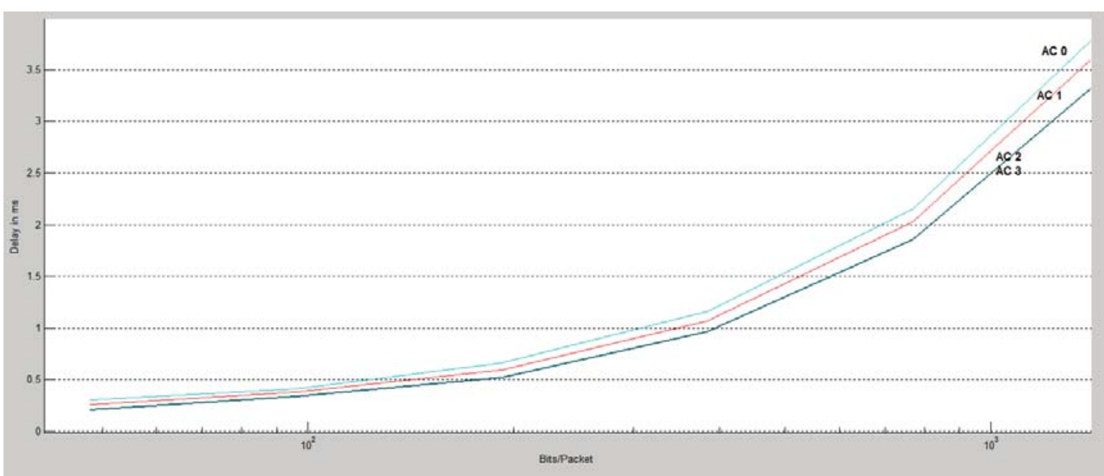

Figure 6-20 Average Delay for Instance-1

Analysis: Firstly, we can observe from the above chart that, according to the increase of packet size, the delay for each AC will also increase, whereby AC 3 and AC 2 are almost overlapping each other as well as AC 0 and AC 1 being slightly higher. Such a phenomenon can be explained by breaking up overall delay into two parts: constant and variable from the view of packet size. The former refers to media access delay, including frame spacing period and Backoff, propagation delay that is irrelevant with packet size but is mainly dependent on the number of ACs, packet generation frequency and transmission distance. The latter is the process and queuing delay at both the transmitter and receiver end, which is immediately affected by the size of packet.

Since our previous simulation only involves three vehicles and that there is no collision happening when checking “collision status” from OPNET, the overall delay is completely dominated by packet size, and the impact of AC priority will be diluted by the increase of packet size. For instance, at 48 bits/packet, the delay of AC 0 is 1.5 times that of AC 3, but is only 1.138 times in the 1400 bits/packet situation. Furthermore, by analysing collected delay data, we found that there are approximately 0.23ms increases per every 100 bits added on packets, despite what the kind of AC or base packet size is. Table 6-3 shows a detailed ration for each AC.

Table 6-3 Increased delay per 100 Bits Added (ms/100 bits) of Instance 0

Delay Added (ms)	96	192	384	768	1400
AC 3	0.26672917	0.18927708	0.23186146	0.23210938	0.23167563
AC 2	0.26666667	0.18822917	0.23239583	0.23239583	0.23275316
AC 1	0.24291667	0.22197917	0.24802083	0.24804688	0.24844937
AC 0	0.23020833	0.25822917	0.25838542	0.25835938	0.25878165

One thing needed to be pointed out here is that it is pretty hard to get delay increase per bit value, since suddenly stepping up may happen due to the padding mechanism of the OFDM symbol. For example, under QPSK (48 bits per symbol), there will be no delay difference between 20 bits/packet and 40 bits/packet, and an abrupt surge might be seen when deploying 50 bits/packet.

In general, we can conclude that increasing the packet size in batch has an approximately linear impact on network delay. Meanwhile, the higher packet size is the smaller difference of delay performance between ACs.

6.5.3 Analysis of Instance-2

Concerning instance 2 and 3, their statistical data can actually be obtained from the same simulation scenario and just two different study aspects, i.e. one AC to three other ACs; three ACs to one AC. In order to study the impact of bother packet size and the media contention mechanism on VANET performance, we alternately set one AC range from 48 to 1400 bits/packet and the remaining three ACs to contain 384 bits/packet. Table 6-3 briefly introduces four sub-instances of our study.

Table 6-4 Packet Size Configuration for Four Sub-Instances

	Packet Size (bits)			
Sub-Instance No.	**AC 3**	**AC 2**	**AC 1**	**AC 0**
0	48-1400	384	384	384
1	384	48-1400	384	384
2	384	384	48-1400	384
3	384	384	384	48-1400

After running simulation around 24 times, detailed data for each sub-instance is put in the Appendix, whereby each average delay data is obtained from at least the thousand sampling points. Meanwhile, they provide great help for our comprehensive study of packet size impact on VANET performance.

Firstly, we examine the delay of each AC, along with an increased packet size under the media contention mechanism. Figure 6-21 illustrates the performance of each AC.

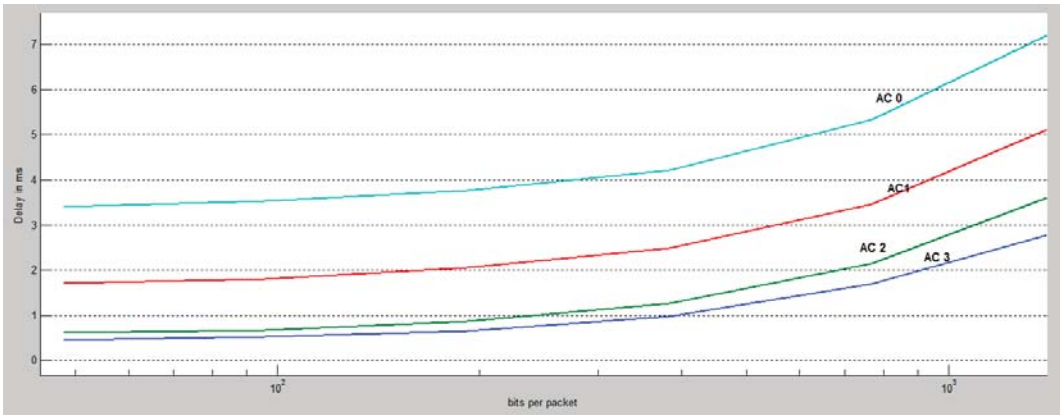

Figure 6-21 Average Delay of ACs for Instance-2

Analysis: By comparing with Figure 6-20, it can be seen that each AC expends its spacing with one another, especially AC 3 and AC 2, which are almost overlapping in Figure 6-20, yet represent a noticeable distance in Figure 6-21. Such spacing is mainly due to media access delay varying with AC types under contention. As we know, under the EDCA mechanism, AC with higher priority will suffer smaller frame spacing and contention backoff, thus resulting in AC 3 starting from a low Y axis value, in contrast to its counterpart (AC 0). On the other hand, unlike previous instances, the same amount of bits added to different ACs under media contention generated variable extra delay, whereby AC 3 experiences the lowest delay increase at around 0.168 ms per 100 bits, in comparison with the 0.269 ms of AC 0. Detailed rates are listed in Table 6-4, as follows:

Table 6-5 Delay Increase per 100 Bits Added

Delay Added (ms)	96	192	384	768	1400	Average
AC 3	0.160625	0.156979	0.166094	0.181276	0.178307	0.168656
AC 2	0.180208	0.2225	0.190417	0.233724	0.236978	0.212765
AC 1	0.217708	0.2375	0.240052	0.252526	0.259351	0.241428
AC 0	0.2925	0.229896	0.247708	0.283594	0.294636	0.269667

All these phenomena indicate one principle, which is that EDCA is a quite robust mechanism under media contention, under which AC with higher priority will be less affected by the impact of increasing packet sizes. Also, through comparing the data of the highest and lowest delays across ACs, it can be found that, as long as the size of the packet is confined to 1400 bits, the delay of AC3 will always be lower than AC 0, as the maximum value of the former under the three vehicle situations is 2.843 ms, which is much less than 3.3863 ms, the minimum delay of AC 0. Whether this is still true under more vehicles will be examined later on.

6.5.4 Analysis of Four Sub-Instances of Instance-3

Next, we check the impact of a packet size increase from 48 to 1400 bits/packet of a certain AC on the other three ACs. Figure 6-(22~25) illustrate these four sub-instances.

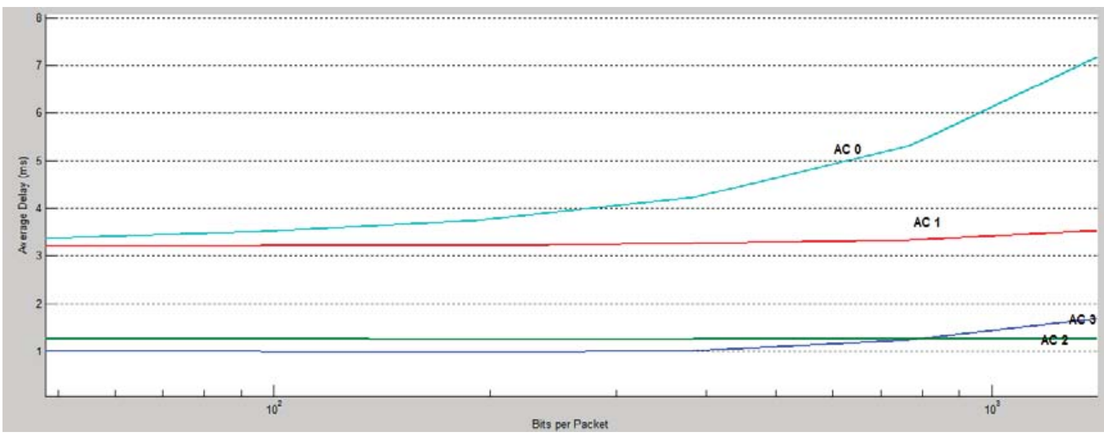

Figure 6-22 Impact of Packet Size of AC 0 on VANET (sub-instance 0)

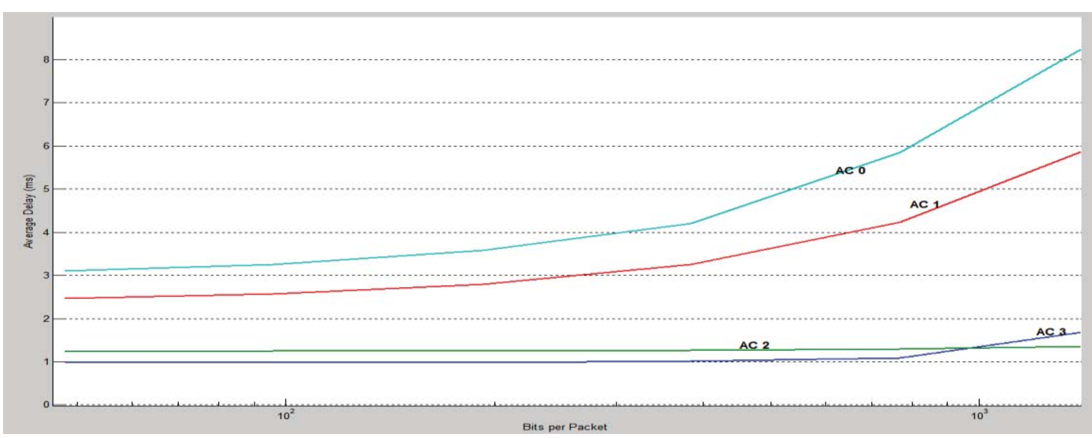

Figure 6-23 Impact of Packet Size of AC 1 on VANET (sub-instance 1)

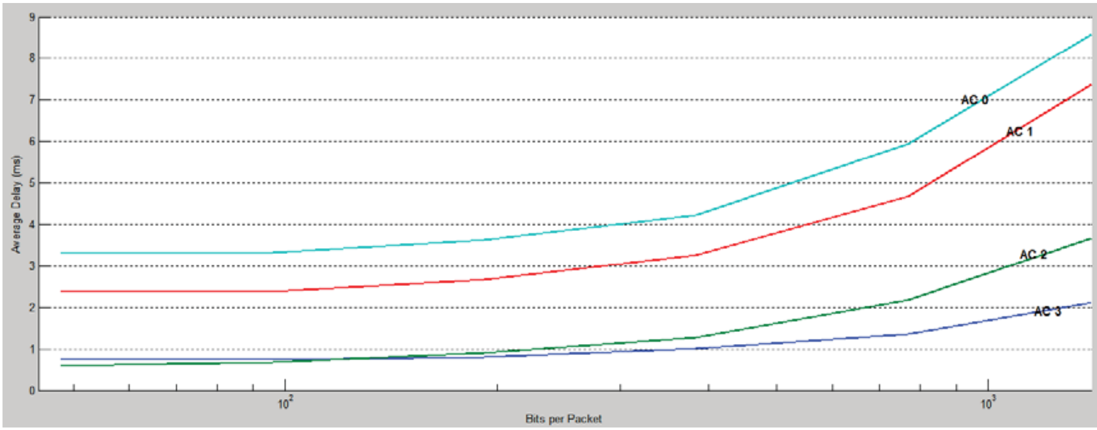

Figure 6-24 Impact of Packet Size of AC 2 on VANET (sub-instance 2)

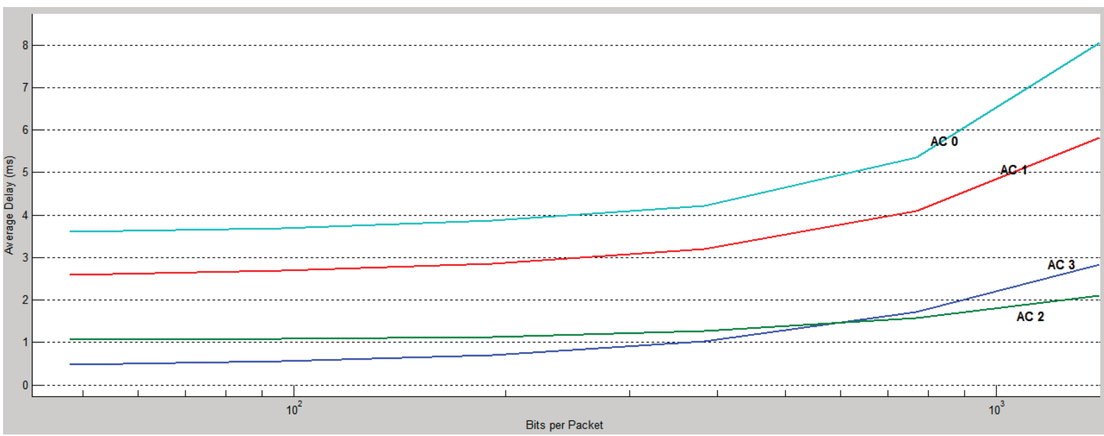

Figure 6-25 Impact of Packet Size of AC 3 on VANET (sub-instance 3)

Analysis: These four diagrams together illustrate some interesting phenomena of the impacts of packet size of different AC on VANET performance. Table 6-5 gives an overview of the average increased delay/100 bits for these four sub-instances.

Table 6-6 Average Increased Delay /100 bits for Four Sub-instances

Average Increased Delay (ms)	Sub-Instance 0	Sub-Instance 1	Sub-Instance 2	Sub-Instance 3
AC 3	0.022829509	0.024183544	0.075627044	0.168656184
AC 2	0.002476332	0.010266812	0.212765361	0.067404931
AC 1	0.022600672	0.241427545	0.273015164	0.212292524

AC 0	0.269666799	0.357498945	0.306356013	0.251460509

These rules can be summarised and explained based on the data collected from our simulation, as follows:

1. Increasing the packet size of the different AC will lead to a higher delay for all ACs. However, the magnitude and sensitivity turn out to be unevenly due to the domination of the EDCA mechanism.
2. The packet size of AC 0 impacts on the delay of itself at the greatest magnitude, at an average of 0.269 ms/100 bits, yet impacts a little on AC 2. Concerning AC 3 and AC 1, there would be a noticeable delay increase when the packet size of AC 0 reaches 384 bits/packet, and AC 3 would suffer a relatively bigger delay increase than AC 2, even though it might seem out of expectation, since AC 3 is with the highest priority and would be the most resistant one against impacts of other ACs. Such a phenomenon could be attributed to the shielding effect. Although AC 0 is with the lowest priority, it still has a minor opportunity to gain media access, which is actually bigger under the fact of a low packet generation frequency in VANET. When its packet exceeds a certain level, the process time will be remarkably increased, which causes two results: firstly, one or more AC 2/1 packets might be generated and will compete with AC 3. Secondly, a newly generated AC 3 packet cannot process backoff countdown, but will instead wait in the queue. The issue is that AC 3 ranks at the highest priority, whose queue delay is comparatively smaller than counterparts of other ACs, but is vulnerable to an increasing process delay caused by other ACs. In short, when there is a negative impact on network performance, the AC with the higher priority will stand on the front line, in order to digest such impacts, e.g. like a shield or cushion.
3. The packet size of AC 1 has the greatest impact on the delay of AC 0 at an average 0.3575 ms/100 bits, due to these two ACs being relatively competitive in the EDCA mechanism. Also, it has the second largest impact on itself, followed by AC 3, and has almost no effect on AC 2, due to the shield effect.

4. The packet sizes of AC 3 and 2 have a similar and most prominent impact on all ACs in VANET. If we divide ACs into high and priority groups, which contain AC3/2 and AC 1/0, respectively, the rule can be described that increasing the packet size of one AC in a higher priority group always affects AC 0 at the largest scale, as well as has the smallest impact on its counterpart in the same group, namely AC 3 or AC 2. Meanwhile, there is also a considerable delay increase of itself, as in our simulation, AC 3 and AC 2 reach 0.1686 ms and 0.212 ms per 100 bits, respectively.
   What is stated above provides a practical mean to our practical application of 802.11p, in which we realise that the immediate approach to improved network performance of certain ACs turns out to be reducing the packet size of itself, especially AC 0 and AC 3. Meanwhile, the packet size of the former has the faintest overall impact on the overall performance of ACs, and the latter, however, has the greatest impact, followed by AC 2 and AC 1. Therefore, concerning 802.11p, it would be very helpful if advanced compression was adopted on high priority ACs and thus eliminated non-safety critical information from either their MPDU header or payload area.

Chapter 7 Advanced Scenarios and Performance Analysis

7.1 Study of Vehicle Number Impact on VANET

7.1.1 Deployment and Performance of Instance-4

Next, we study the number of vehicle impacts on VANET based on Instance 1, whereby only three ACs of the same kind are involved. It has to be pointed out that, although we call the factor "Number of Vehicle", we actually mean the number of ACs carried by vehicles, since there might be one or more ACs for each vehicle in the real world. Considering our topic of VANET performance, it would be better to keep using the term "Number of Vehicle", with further annotation on the number and kind of ACs.

In our following simulation (Instance -4), the vehicle number was chosen from 10 to 100, whereby their packet size for AC is based on Instance 1. Therefore, we can predict that the Table of Instance -1 will expand to four larger tables for each kind of AC exclusively. However, whilst studying the impact on individual types of AC, we chose AC 3 and AC 0 only, since it is apparently the performances of AC 2 and AC 1 that will locate between their counterparts at the edge of priority. Furthermore, as mentioned at the beginning of this chapter, through the increase of vehicle numbers, we will monitor not only delay but also the signal collision status on our instance in order to judge the accuracy of data collected. Figure 7-1 illustrates an example topology for AC 0 in a 10 vehicles condition.

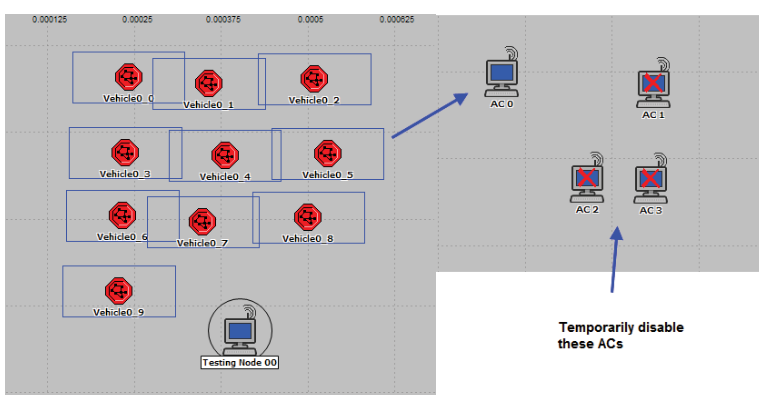

Figure 7-1 Topology of Instance-4 under 10 Vehicle Condition

After running the simulation 120 times under different configuration, we obtained data for both average delay as well as time average collision status, which can be found in the Appendix. The data for average delay of each AC has been picked out and processed by Matlab, in order to represent two 3D diagrams in mesh format in Figure 7-2.

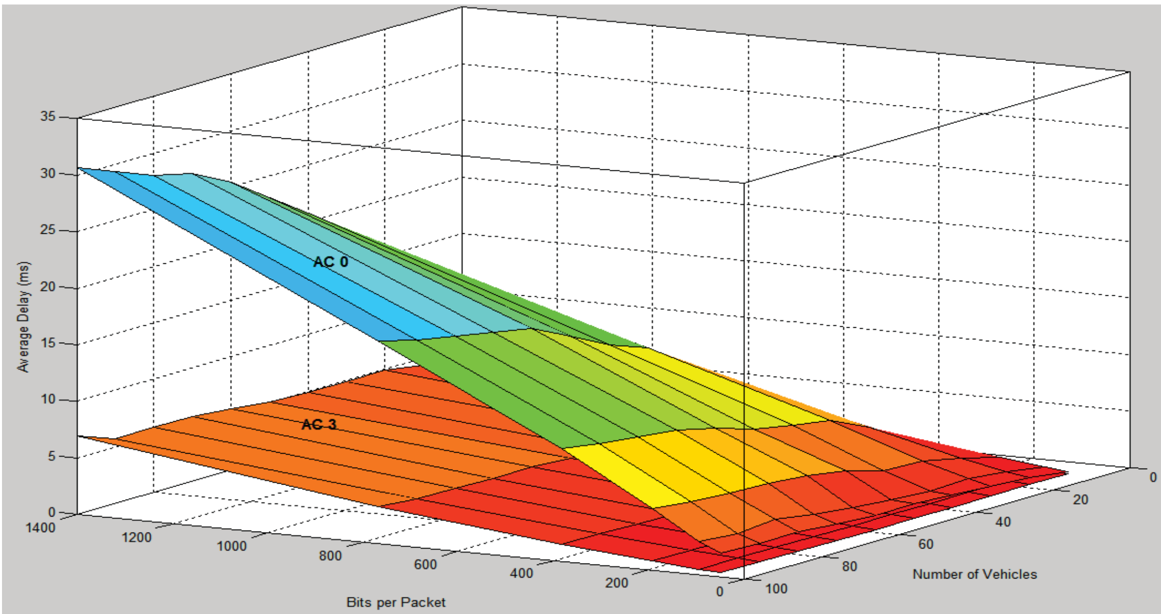

Figure 7-2: Average Delay Based on Vehicle Number and Packet Size in 3D Mesh Format

7.1.2 Analysis of Instance-4

In Figure 7-2, we can see that two non-overlapping curved surfaces for AC 3 and AC 0 respectively exist. From previous analysis, it shows that the packet size of AC has a nonlinear impact on the delay of VANET. In this simulation, we found that, under the same packet size, the vehicle number also contributes to a nonlinear impact on network. These two impacts result in each AC representing themselves in a curved surface in 3D, whereby lots of interesting phenomena can be observed and explained, as below:

1. At any point of (x, y), the value of AC 0 is always higher than that of AC 3. This means that, whilst under the same packet size and vehicle number, the delay of AC 3 is always lower than AC 0. Table 7-1 shows the ratio of delay between these two ACs.

Table 7-1 Delay Ratio between AC3 and AC0

Vehicle Number	Packet Size (bits)					
	48	96	192	384	768	1400
	% of $delay_{AC3}$/ $delay_{AC0}$	% of $delay_{AC3}$/ $delay_{AC0}$	% of $delay_{AC3}$/ $delay_{AC0}$	% of $delay_{AC3}$/ $delay_{AC0}$	% of $delay_{AC3}$/ $delay_{AC0}$	% of $delay_{AC3}$/ $delay_{AC0}$
10	45.30805%	52.68987%	49.07003%	49.49728%	43.52806%	53.43127%
20	26.46045%	27.95734%	32.36207%	33.54552%	30.38885%	36.13730%
30	20.33726%	22.89531%	25.94399%	23.62221%	24.32868%	27.70663%
40	17.79008%	24.93669%	22.19527%	20.34183%	19.67183%	23.45120%
50	15.55578%	24.08680%	17.61468%	18.72852%	19.63963%	21.65888%
60	17.08029%	20.63362%	15.45850%	18.11852%	18.58024%	21.32377%
70	16.51185%	18.39700%	13.74920%	14.61118%	17.94289%	20.94330%
80	14.36548%	14.82191%	13.95019%	14.97769%	17.59218%	20.54308%
90	16.03093%	16.75482%	14.60256%	14.97141%	17.18188%	19.54115%
100	15.31146%	15.66473%	14.58648%	14.69202%	18.23769%	22.53833%

It can be seen that, when at the lowest vehicle number and whatever the packet size, the difference of delay between these turns out to be the smallest, whereby AC 3 accounts for around half that of AC 0. On the other side, through the general increase of vehicle numbers, the gap is reduced gradually from around 50% to 15 or 22%. Such a phenomenon is because, when media is heavily occupied by the same kind of AC type, AC 3, although with the smallest AIFSN, has to process more deferred access.

2. The collision phenomenon is another complex issue of WLAN and is sometimes considered more important than VANET delay. OPNET provides some indicators, such as “collision status” and “packet marked noise by power stage”, which are all Boolean value and which are recommended to be reviewed in a time average filter; they are also used to examine whether they occur at a certain time point. However, in VANET, every vehicle sends packets in a very discrete manner; such indicators can only show collision increase rather than how exact packet loss will be due to collision. Considering our simulation is always under a free space propagation mode, the number of packets difference between transmitters and receiver must therefore be

caused by collision, which also provides a quantitative method for our study. Meanwhile, DES indicates that, when even under the most condense instances, namely a 100 vehicles at 1400 bits/packet, each vehicle still sends at 10 packets/s equally. After calculating based on Appendix data, the packet loss rate due to collision is listed in Table 7-2 and Figure 7-3 illustrates this data in 3D format.

Table 7-2 Packet Loss Rate for AC 0 and AC 3

Only one AC 0 for each Vehicle						
Vehicle Number	**Packet Size (bits)**					
	48	**96**	**192**	**384**	**768**	**1400**
	Loss Rate	**Loss Rate**	**Loss Rate**	**Loss Rate**	**Loss Rate**	**Loss Rate**
10	12.18167%	15.65781%	15.75667%	23.23333%	28.28333%	31.34000%
20	32.14000%	36.06165%	43.02165%	50.78008%	54.85500%	56.69834%
30	45.02000%	48.47223%	55.86223%	62.63667%	66.47333%	67.83000%
40	53.27875%	57.12250%	63.00668%	68.98418%	73.16000%	74.16168%
50	56.01000%	62.36334%	68.22866%	73.65934%	77.07066%	78.14866%
60	57.46388%	67.63278%	72.93000%	77.32445%	80.06222%	81.05833%
70	62.31547%	69.73953%	73.56286%	78.84047%	82.45096%	83.22904%
80	66.70729%	69.55875%	75.19791%	76.99688%	84.27291%	84.98959%
90	69.26297%	71.70186%	77.32222%	79.10186%	85.23241%	86.19074%
100	72.28917%	74.78167%	79.72250%	81.13250%	85.01667%	85.42500%
Only one AC 3 for each Vehicle						
Vehicle Number	**Packet Size (bits)**					
	48	**96**	**192**	**384**	**768**	**1400**
	Loss Rate	**Loss Rate**	**Loss Rate**	**Loss Rate**	**Loss Rate**	**Loss Rate**
10	21.55667%	32.14000%	40.32500%	51.97120%	58.14600%	66.02500%
20	47.36335%	54.40667%	63.74584%	74.36667%	82.74828%	85.94167%
30	51.92110%	59.99333%	70.86113%	79.78333%	87.35278%	90.62223%
40	56.53750%	66.80418%	75.62708%	82.92085%	88.72292%	91.86458%
50	60.30534%	68.38134%	77.49000%	84.56500%	90.72823%	93.41334%
60	62.12167%	71.71667%	79.85278%	86.70417%	92.39167%	94.47502%
70	66.28286%	75.03286%	81.70119%	87.80833%	92.75239%	95.09040%
80	72.24479%	78.81146%	84.59584%	89.61041%	93.89896%	95.78080%
90	73.07314%	80.63519%	85.40000%	89.88333%	94.18981%	95.88056%
100	75.76167%	82.98250%	86.25083%	90.23750%	94.17333%	95.35167%

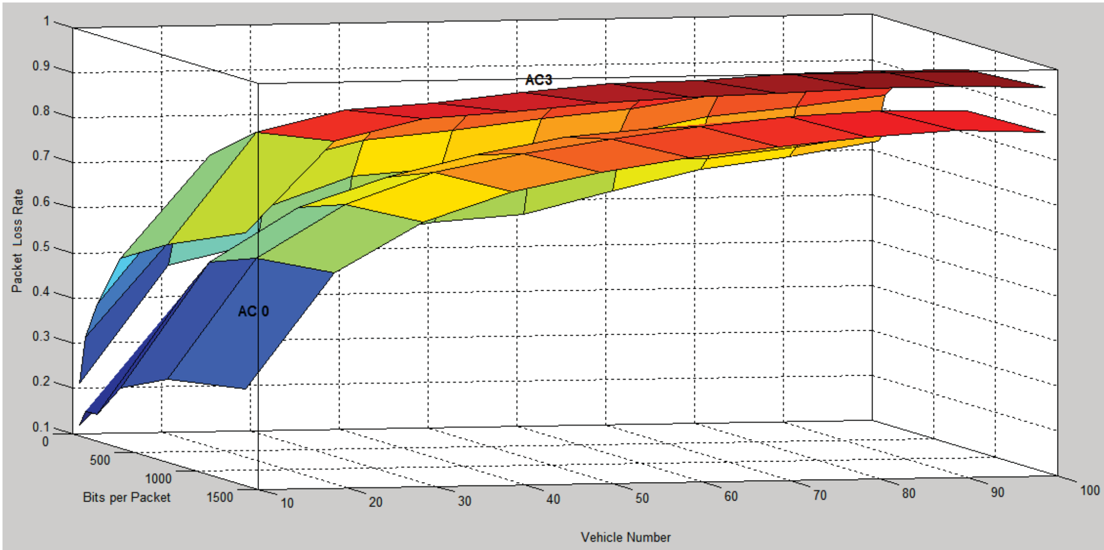

Figure 7-3 Packet Loss Rate of AC 0 and AC 3

It looks like the packet loss rate of either AC 0 or AC 3 at any given packet size and vehicle number might be too high to be feasible for real application. Indeed, there is little possibility of having 100 vehicles sending 1400 bits/packet AC 3 at a frequency of 10 Hz within 2 ms as a guard interval. However, it is necessary to understand that our simulation is only based on an extremely undesirable situation, in which the upper limit boundary and many characteristics of 802.11p for VANET can be observed and studied. Otherwise, we could set two vehicles to send one small size packet every 60 seconds; however, it definitely doesn't help to evaluate the performance.

On the other hand, the mechanism of collision can hardly be explained by several sentences, although we could simply say that a larger number of vehicles or packet sizes of VANET will increase the packet loss rate; however, it is worthy of examining in detail and is provided as follows:

First and foremost, it is important to understand that there are two kinds of network models for a collision study - saturated and non-saturated - whose difference relies on whether each node always has packets to be sent from a queue [62]. There is remarkable research of the former by Giuseppe Bianchi, which was published in 2000 and which was widely adopted. Concerning the non-saturated network, it has only just been studied in recent years, due to the emergence of Wimax technology, and has turned out to be much more complex, in contrast with its counterpart, while also sharing lots of similarities. Even though our simulation is based on the relatively worse VANET operation situation of CCH, it is still a type of non-saturated network, as vehicles always send 10 packets/s, which is identical to what has been loaded from the MAC layer. In real application, the packet generation frequency obviously will be lower statistically, thus making its type firmer. Therefore, we can conclude that VANET should always be a non-saturated one under its CCH.

Next, we list an equitation of collision probability for these two network types, which has a linear relationship with packet loss rate. For instance, if packet transmission rate is at 10 per second, and collision probability is 30%, we know that there are 3 packets/s lost. Meanwhile, a special case for broadcasting will also be derived, in which we can consider that CWmin=CWmax and that there is no retransmission, i.e. there is only one time backoff for every packet. According to [63] and [64]:

Saturated Network:

$p = 1 - (1 - \tau)^{n-1}$ (Equation 7-1)

$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)}$ (Equation 7-2)

p: Collision Probability; n:Number of Transmitting Nodes; τ :Transmission Probability; m:Maximum Backoff Stage

In the broadcast mode, apparently m=1, thus transmission probability can be simplified as

$\tau_{broadcast} = \frac{2}{1+W}$ (Equation 7-3)

Non-Saturated Network:

$p_{u1} = p_b(1 - (1 - \tau_t)^{N_t}(1 - \frac{1}{W_u})^{N_{u1}}(1 - \tau_{u2})^{N_{u2}})$ (Equation 7-4)

$$p_b = 1 - \frac{a_i' T_i}{E[Y_u]}$$

$N_{u1} = (N_u - 1)\lambda(2E[T_{res}] + p_b(W_u - 1)E[Y_u])$ (Equation 7-5)

$N_{u2} = N_u - N_{u1} - 1$

$\tau_{u2} = (\frac{p_{u1}}{1 + p_{u1} - p_{u2}})\tau_u$

p_{u1}: Collision probability of first backoff attempt

N_t: Number of saturated nodes

W_u: Initial contention window

p_b: Probability that an arriving packet at a non – saturated station finds the channel busy

N_{u1}: Average number of new packets from other non – saturated stations that come during W_u

N_{u2}: Average number of packets on their retransmission attempts from other non-saturated stations

τ_{u2} : Probability that a non-saturated station attempts to retransmit in a given slot

Other symbol meanings can be found in [64] and are left out here.

Referring to the broadcast mode, N_t and N_{u2} should be zero. Thus, the above equation can be written as:

$p_{u1} = p_b(1 - (1 - \frac{1}{W_u})^{N_{u1}})$ [Equation 7-6]

Although these equations provided seem delicate and complex, especially for a non-saturated network, their characteristics can generally be described as follows:

In a saturated network, the collision probability is dominated by CW and the number of nodes, rather than AIFSN or packet size, although it sounds odd. We have proved this in OPNET by setting the packet generation frequency to be 1MHz in two packet size instances: 48 bits and 480 bits/packet (10 vehicles) and two AIFSN instances: 2 and 5; the results are exactly the same at a packet loss rate of around 85.26%. The reason for such characteristics is because the overall duration for obtaining media access can be divided into three parts: start time, deferred access and CW backoff. These are illustrated in Figure 7-4.

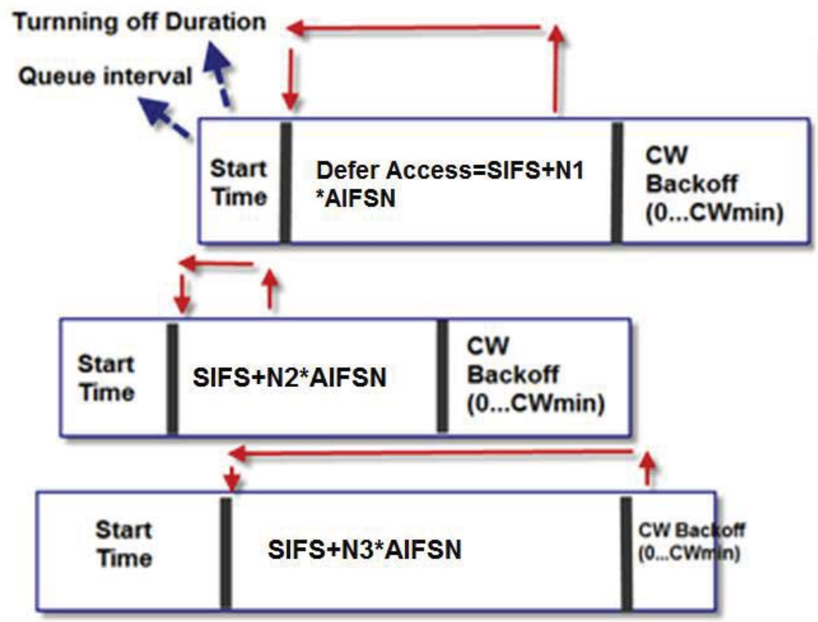

Figure 7-4 Division of Overall Waiting Duration

It might look like a simple diagram; however, it contains essential information for a collision mechanism. The first part (start time) can be subdivided into an initial transmitter turning off duration as well as an interval for a packet arriving at the queue. Apparently, in a saturated network, the latter is always zero. Meanwhile, if we make the former higher, i.e. allocating less overlapping time slots for each vehicle, there should be fewer collisions happening equal to reducing vehicle numbers. In a saturated network, where a queue interval is almost zero for every AC, the overall waiting duration would rely more on turning off duration, deferred access and CW backoff. On the other side, since there is always a packet in the queue for transmission, the turning off duration can only help packets from different vehicles to space each other in a very short duration, due to quick consumption, which is the reason why we see there being fluctuation at an initial stage of our simulation. Figure 7-5 shows such a phenomenon.

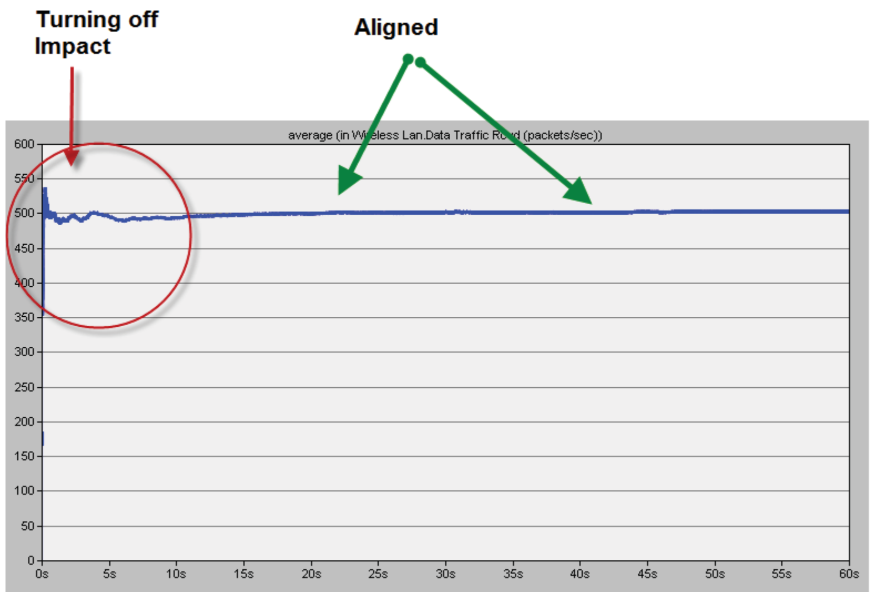

Figure 7-5 Turning Off Impact on Packet Loss at Initial Stage

From the above diagram, we found that, after the initial stage, the packet loss value reached a stable level. This is because, after the first packet has been sent, it will instantly be replaced by a new packet that is waiting in the queue, which quickly makes all packets, although belonging to different vehicles, align to the same time point for media contention. In a homogeneous AC case, where duration of deferred access is the same, only CWmin is the dynamic factor distinguishing overall waiting duration for each vehicle. For instance, if our simulation is under saturated configuration, the transmission probability τ of AC 0 for each vehicle in a broadcast will equally be 2/(1+15)=1/8, which is irrelevant to the vehicle number. Meanwhile, through the increase of vehicle numbers, more of them will be assigned the same CW, due to limited CW variances, thus causing collision instances on an exponential scale. These rules are generally true for both saturated and non-saturated networks and therefore explain why the results of our simulation show that, whilst under the same packet size, the packet loss rate increases according to there being more vehicles involved. For instance, at a packet size of 48 bits, the loss rates of 3 increase gradually, from 12.18% (10 vehicles) to 72.289% for AC 0 and from 21.55% (10

Vehicles) to 75.76% for AC 3, respectively. In Table 7-3, we provide a comparison of their collision rates.

Table 7-3 Collision Rate Comparison AC 3/AC 0

Vehicle Number	Packet Size (bits)					
	48	96	192	384	768	1400
	AC 3/AC 0	AC 3/AC 0	AC 3/AC 0	AC 3/AC 0	AC 3/AC 0	AC 3/AC 0
10	1.769598914	2.052649764	2.559233645	2.236924281	2.055839959	2.10673261
20	1.473657436	1.50871258	1.481715253	1.464484991	1.508491022	1.515770525
30	1.153289649	1.23768453	1.268498037	1.273748071	1.314102547	1.336019952
40	1.06116416	1.169489693	1.200302706	1.202027132	1.212724405	1.238706953
50	1.00766888	1.096499001	1.135739732	1.148055359	1.177208466	1.195328749
60	1.08105584	1.060383192	1.094923671	1.121303374	1.153998359	1.165518844
70	1.063666143	1.07590141	1.110630947	1.113746928	1.124940073	1.142514675
80	1.08301192	1.133020109	1.124975876	1.163818824	1.114224677	1.12697101
90	1.055010317	1.124589988	1.104469033	1.136298671	1.105093863	1.112422873
100	1.048036241	1.109663638	1.081888175	1.112223831	1.107704324	1.116203301

Furthermore, an inversely proportional relationship between CW and τ means that, when at the same vehicle number and packet size situation, the loss rate of AC 3 is always higher than AC 0, which is represented in two non-overlapped curved surfaces in Figure 7-3.

Next, we checked the non-saturated network. The three main factors which dominate its collision probability are p_b, N_{u1} and W_u, whose meanings have been described previously. Although it looks a bit complicated involving many sub factors, we found that its concentration diverted from merely a node number in the saturated network to packet numbers arriving in the non-saturated network. Thus, the exponential variable of Equation 7-1 has been replaced by N_{u1}, which represents how many packets come to the network within W_u, which further implies that, in a non-saturated situation, packet size and generation frequency have great impacts on collision rate, together with coefficient p_b enhancing such a relationship. The reason behind a factor changing is that, in a non-saturated network, every node is sending packets in a discrete manner and does not involve media contention all the time, i.e. active or inactive, thus making it impossible to simply use an overall node number for the collision study. In general, a longer duration will be required to send larger packets, which can cause more vehicles to have packets in their queues for transmission and content media after a certain node finishes the sending. One thing which needs to be pointed out is that the initial CW contributes to both base and exponential factors of Equation 7-6, and thus performs a slight offset impact on bigger CW. For instance, although the CWmin of AC 0 is 15 resulting in a base value of 1/15, it might encounter more new packets arriving due to a longer backoff duration, i.e. bigger N_{u1},which is different from the saturated situation. However, such an offset impact can be quickly overwhelmed by an increasing value of vehicle numbers, which is the reason why we still see there are two exponential functions, like 3D diagrams, in Figure 7-3. All these stated above explain why, in the same 10 vehicles instance, AC 0 with 1400 bits/packet experiences a 2.57 times loss probability as big as 48 bits/packet. Moreover, even though there is a considerable AIFSN and CWmin difference between AC 0 and AC 3, their collision performances are getting closer when we increase the value of the number of vehicles, as can be seen in Table 7-3.

3. There was an interesting phenomenon in our simulation; through reviewing delay data collected in the same packet size, occasionally the delay of a higher vehicle number was smaller than its counterpart of a smaller number. For instance, with 192 bits/packet, the delay of 30 vehicles and 40 vehicles was 0.7054 and 0.6376 ms, respectively, and such a situation only happens once at AC 0 at vehicle 30/40 with 96 bits/packet. At first glance, it might seem very confusing and can be blamed on incorrect configuration. However, after I spent a week simulating sub instances more than 360 times on OPNET, I noticed that it can always happen in certain different areas of the data collection table. After recalling the collision mechanism discussed previously as well as the higher value of “packet marked as noise by power stage” observed from OPNET DES, it is believed that such a phenomenon is due to collided packets, which causes a combined signal either at a higher or lower power.

Concerning the latter instance, if the power is lower than the packet reception threshold, transmitters in VANET will consider the media to be free and will conduct a media access procedure. On the other hand, we review the statement of "increasing vehicle numbers", which are expected to bring more contention nodes and ultimately dilute the transmission probability. However, for AC with a high priority, especially AC 3 with only 4 kinds of CW variances on the CCH mode, for the small start time, which we set as 2 ms, the number of vehicles encountering collisions is predicted to happen in batches, i.e. there are a high percentage of vehicles transmitting simultaneously. Since VANET on CCH is a typical non-saturated network, after these vehicles send their packets, they might have no more packets in the queues for transmission, thus resulting in actually less vehicle content in the media at the next stage. Finally, the collision also causes there to be a scarce amount of data collected, as we can see from the Appendix, whereby, for instance, only 46.8 packets have been received per packet, thus making a sort of inevitable accuracy in the data analysis. The points stated above explained the observed abnormal phenomenon and it is supposed to appear in a random manner. However, we assure it will appear at a higher probability on AC 3 than its lower priority counterparts.

7.2 Study of Multiple AC Types Impact

7.2.1 Introduction and Performance of Instance-5

Previous simulation instances generally take single AC types for study. However, in real practice, since each vehicle is able to carry multiple ACs, we developed instance-5, which was based on scenario-4, in order to further study the performance in this situation, while also taking real traffic flow into consideration.

As in Auckland, New Zealand, most highways have three lanes for each direction, which is the base of the instance-5 simulation. Meanwhile, according to [65], in a traffic congestion period, one direction is fed at a rate of 6000 vehicles/h and the speed is around 60 Km/h, which is in contrast to the opposite direction of 2000 vehicles/h (100 Km/h). Thus, we estimate that, during this period, there are 133 vehicles within a 1 Km effective coverage. Concerning packet size, it will be chosen at the same pacing as with instance-4. After running the simulation, the collected data is provided in the Appendix. Figure 7-(6~10) gave the performances.

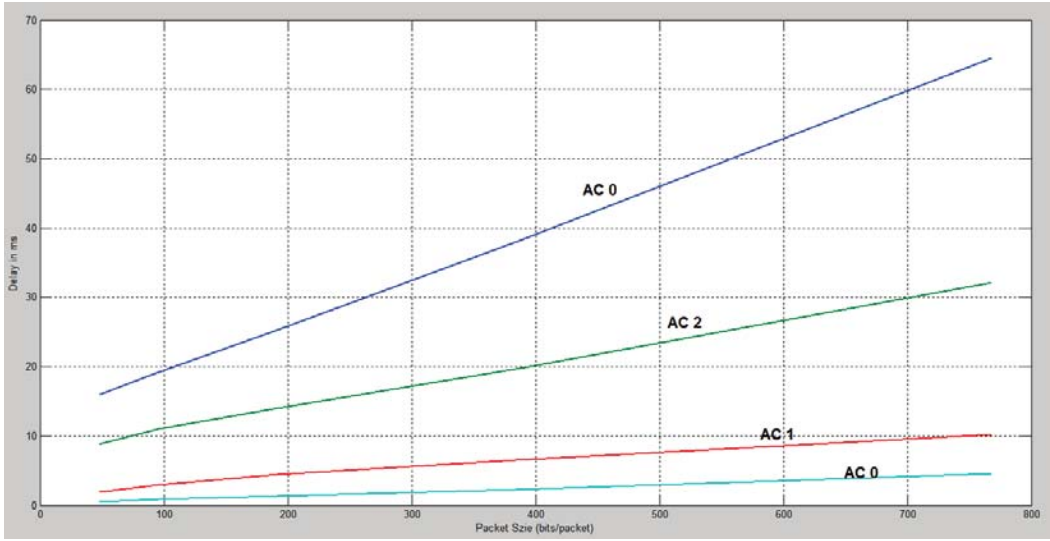

Figure 7-6 Average Delay of ACs under (48~768) bits/packet (Instance-5)

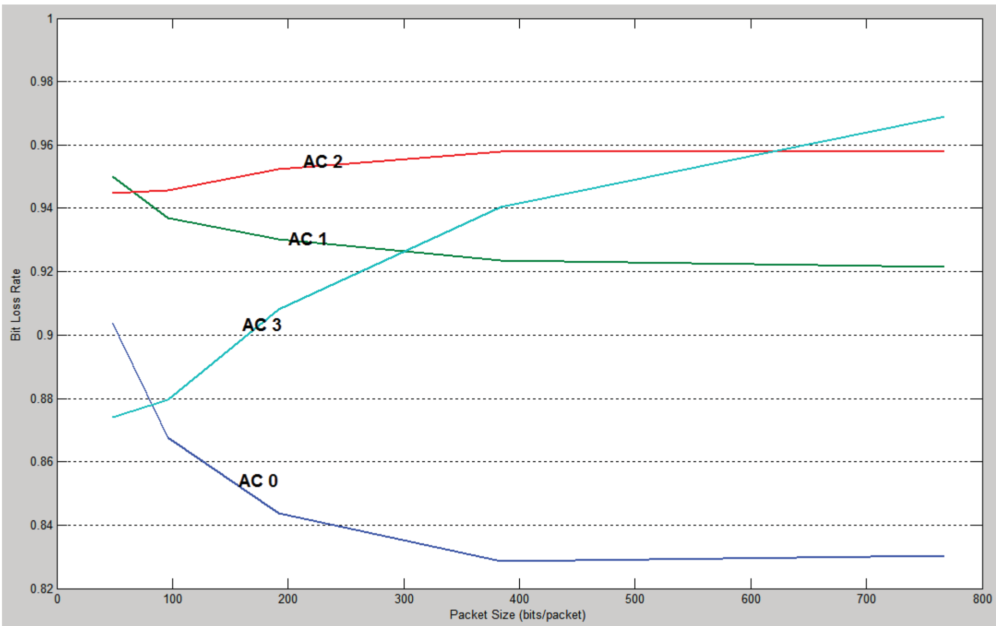

Figure 7-7 Average Bit Loss Rate of ACs (48~768) bits/packet (Instance-5)

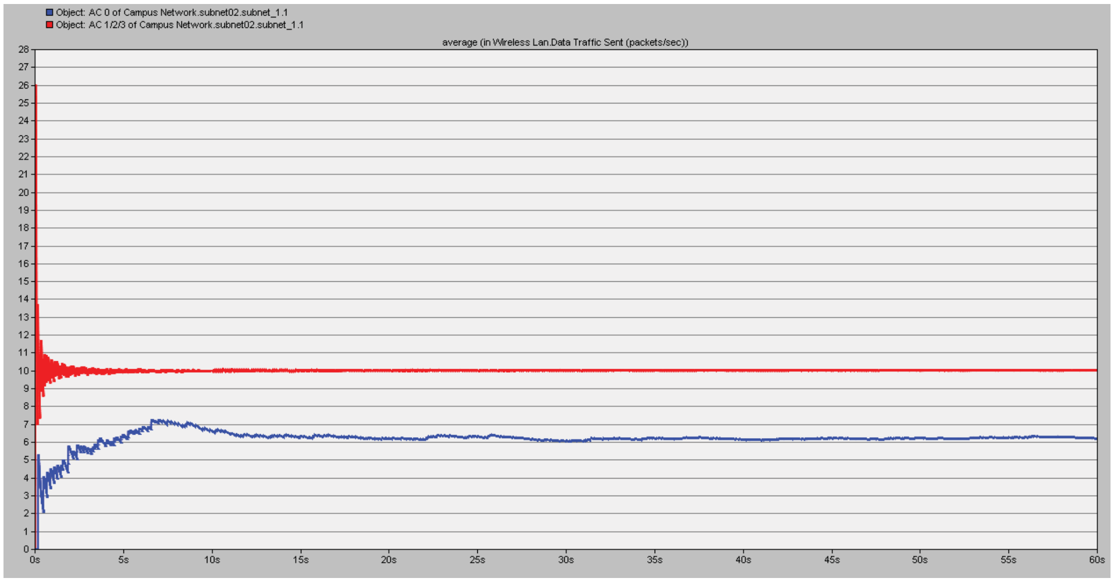

Figure 7-8 Average Packets/s of AC 0 and AC 1/2/3 under 1400 bits/packet

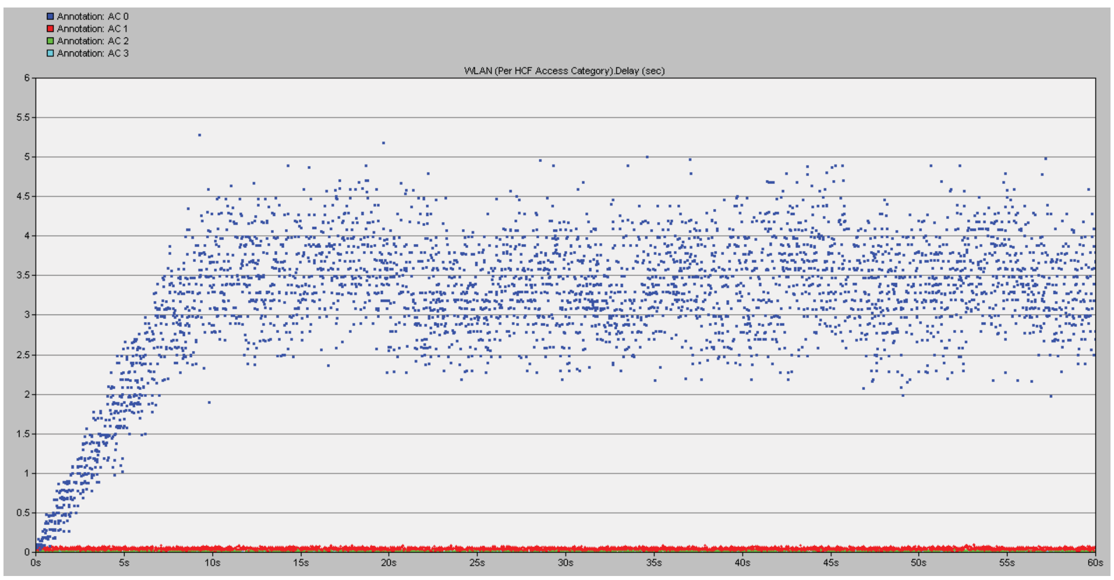

Figure 7-9 Delay of ACs under 1400 bits/packet

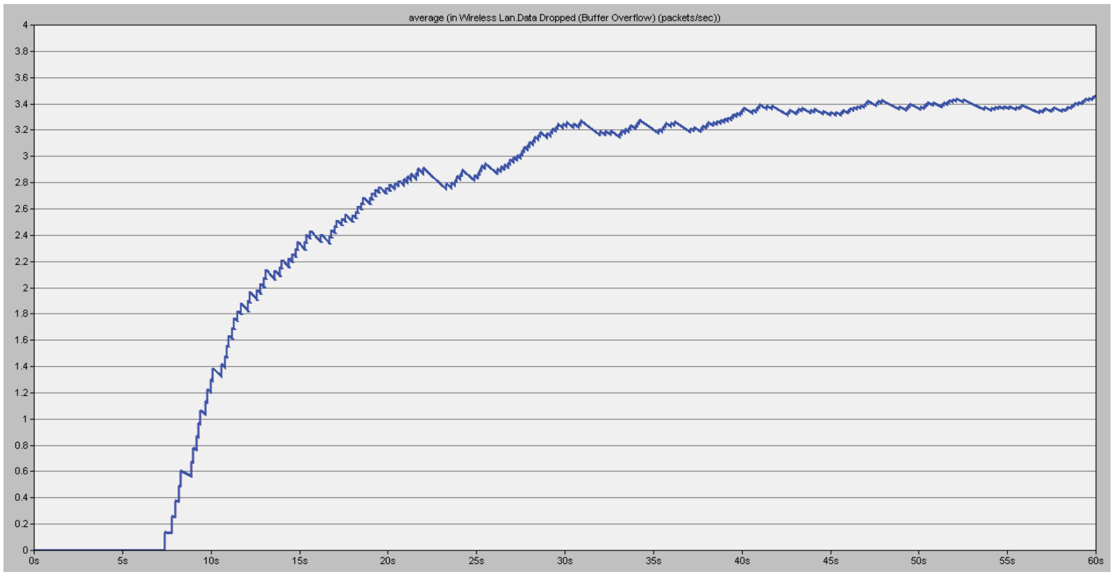

Figure 7-10 Average AC 0 Packet Dropped Per Second under 1400 bits/packet

7.2.2 Analysis of Instance-5

It seems that, from 768 bits to 1400 bits per packet, the network reaches a saturated status. Thus, we individually give the performances two major packet size categories, namely 48～768 bits/packet and 1400 bits/packet. Meanwhile, unlike the signal type of the AC situation, instance-5 with multiple ACs represents in a more complex manner.

In respect to 48-768 bits/packet, we can see that there is a linear relationship between packet size and delay that is similar to instance-4, where lower priority AC will suffer a higher delay. On the other hand, since OPNET is not capable of providing how many packets are received for each AC under multiple AC types, we have to use a bit loss rate instead, although it will be a bit lower than the packet loss rate under the same condition. It is surprising to find that the bit loss rates of AC 0/1 decrease under a packet size increasing from 48 to 368 bits/packet and reach a plateau after that, whereas AC 2/3 gave completely opposite performances. This is because, with the same packet transmission rate for each AC being at 10 packets/s, AC with a lower priority has a greater probability of colliding with other types of AC. For instance, the Packet of AC 1 tends to collide with its counterparts from AC 2/3 and itself, rather than AC 0, due to distinguishing EDCAFs. Meanwhile, from table 7-2, we can see that AC with a higher priority is more sensitive to the increase of packet size in terms of collision, which indicates that packets of AC 2/3 are supposed to collide with the same types of AC as well as with themselves. Thus, such a mechanism is equal to the release of a sort of media resource to a lower priority AC 0/1 and it will decrease their collision probabilities. Moreover, the observed plateaus are due to a much less impact of packet size to the collision rate of AC 0/1.

The performances of VANET under 1400 bits/packet are significantly different from that of 48～768 bits/packet because the network becomes saturated, whereby AC 1/2/3 tend to continue the rules and performances of previous packet size categories. However, there is an abrupt deterioration of AC 0, as not only its packet transmission rate reduces to an average of 6 packets/s; there is also an increasing packet dropped rate due to overflow after 7.5s. All of these phenomena are due to heavily occupied media by AC 1/2/3 in which AC with the lowest priority gains a very faint transmission opportunity and has to drop increasingly accumulated packets in its queue, together with a definitely unacceptable average delay value of around 3.5s.

7.3 Comprehensive Performance Study in Dynamic Environment

7.3.1 Deployment and Performance of Scenario-5

In this sub-section, we are going to extend our simulation into a dynamic environment. The reason we are doing this is merely that 802.11p does not apply to the vehicle network, since it theoretically can resist a velocity of up to 350 Km/h and also every dynamic duration can be divided into thousands of snapshots; however, it can facilitate our study by observing mixed changeable factors in one scenario. In order to do this, we set up simulation scenario-5, which contains two vehicle groups (01 and 02). These groups contain 40 vehicles each with four ACs (48 bits/packet), whose other is identical with scenario-4. Furthermore, in order to avoid a possible edge effect, the dimension of each vehicle group is set at 2000*10 m, whereby vehicles are almost evenly spaced and three testing nodes are deployed (two at the edges and one in the middle, which are marked as 00/02 and 01). The trajectory ranges from

(1000, 100) to (9000, 100) and is only attached to vehicle group 01 at a relative speed of 120 Km/h. Also, vehicle group 02 is fixed at the middle of the trajectory for the purpose of accelerating the OPNET simulation speed. Figure 7-11 illustrates the topology for scenario-5.

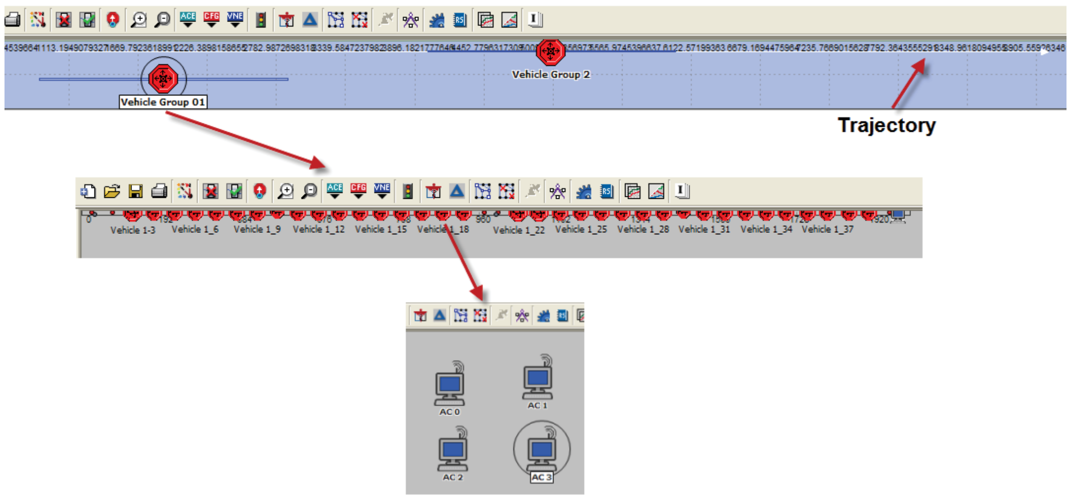

Figure 7-11 Topology of Scenario-5

After running the above simulation, the performances collected from testing node 01 in the middle of the vehicle group are given in Figures 7-12/13.

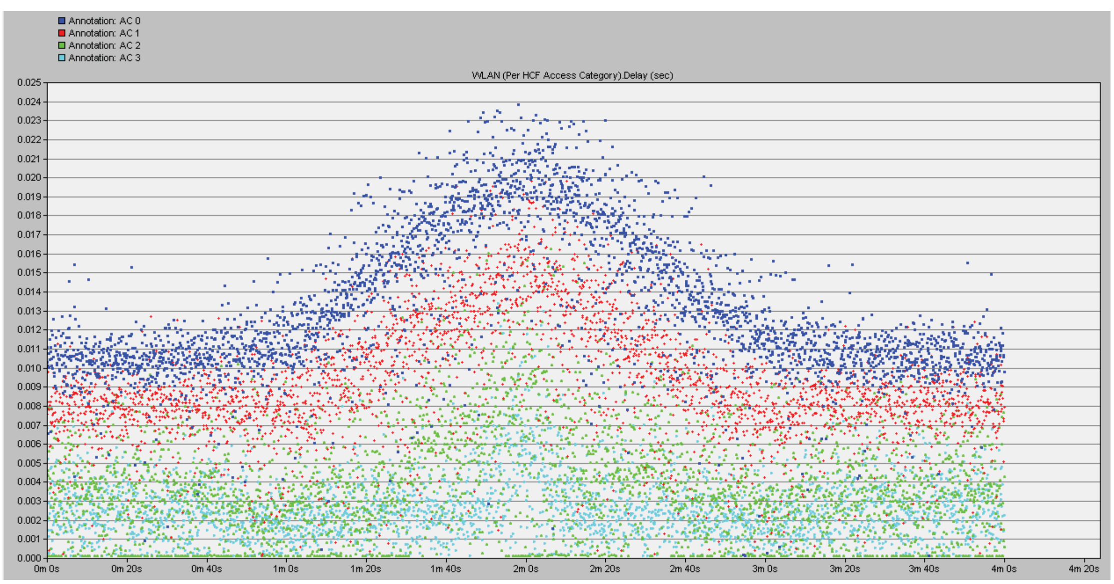

Figure 7-12 Delay of Each AC for Scenario-5 in Discrete Format

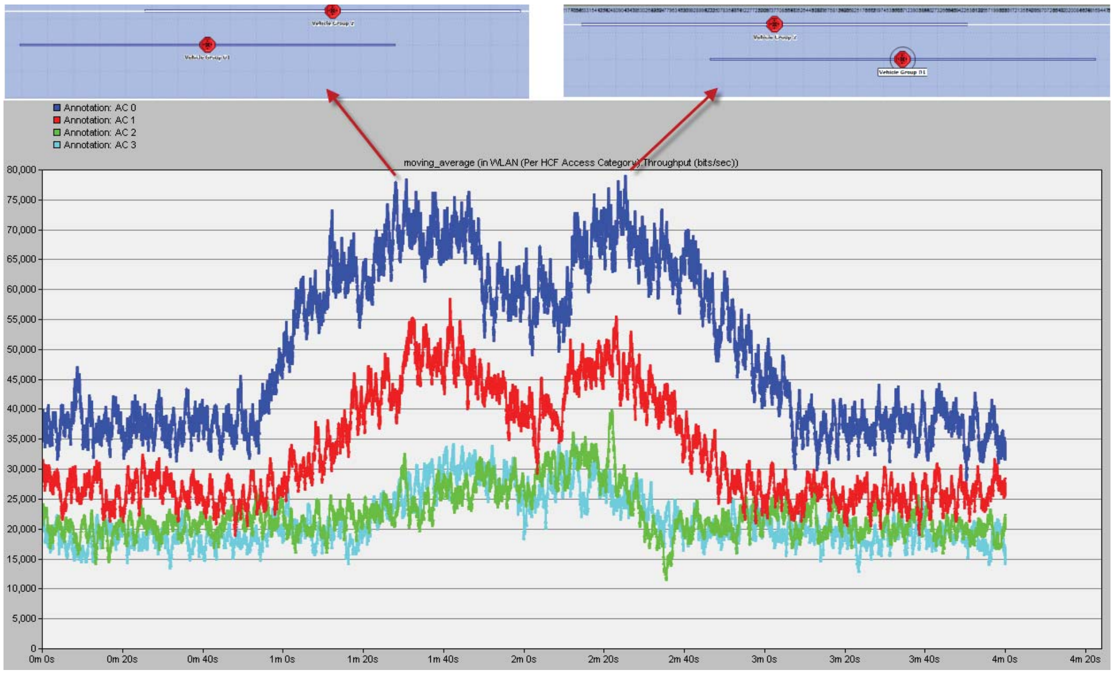

Figure 7-13 Moving Average Throughput of Testing Node 01

7.3.2 Performance Study of Testing Node 01

Firstly, we found that the diagram for delay represents itself in a bell-shaped curve, which can be divided into three main parts: two lines and one parabola. The former are due to vehicle group 01 moving from the point far enough from the left edge of vehicle group 02. Therefore, vehicles have content media with counterparts only within their own group and also provide a stable performance within 1 minute. After that, the two groups start to overlap gradually, which can be considered as more vehicles merging into each vehicle group. Figure 7-14 illustrates the case.

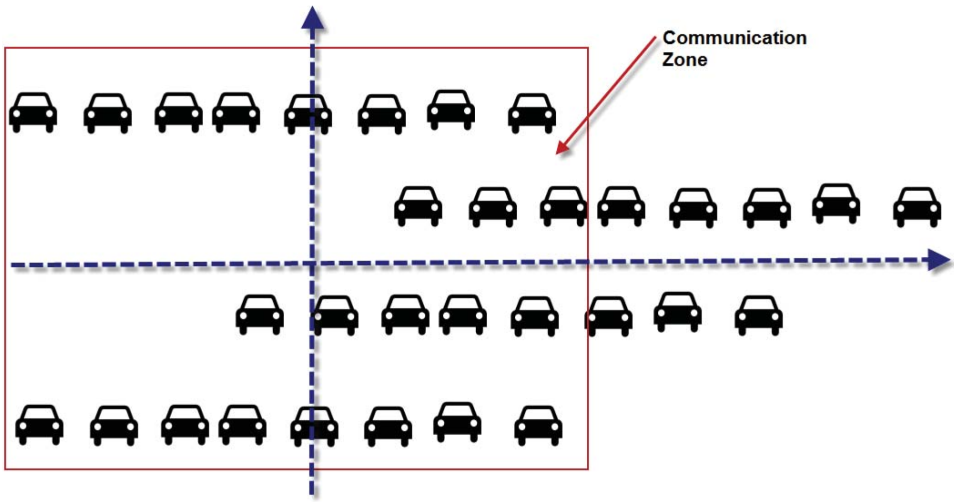

Figure 7-14 Illustration of Vehicle Merge

From the view at the centre of effective communication coverage, vehicles there will experience a greater traffic feed externally, i.e. more vehicles come inside. In our scenario, only group 02 can fill with a 2 Km long effective communication coverage. Thus, the peak delay we saw happened in the 80 vehicles per group situation. Such a phenomenon might look simple, but has an important meaning, which implies two different VANET performances in congested and loosened traffic situations. Concerning the first case, where vehicles are almost continuously fed into certain coverage, the delay would be relatively low but would maintain at a stable level, which helps vehicles in this range precisely evaluate the situation more and also conducts AC adjustment accordingly, such as packet size or generation frequency, for the purpose of enhancing some AC communication quality. On the other hand, the latter instance subsequently causes large-scale fluctuation and jitter. It is necessary to be understood that, since CCH works in the broadcast mode, it is hardly possible to obtain information about a communication environment during that period, but would count in the SCH period, whose establishment, however, completely depends on the successful communication of WSA at AC 0, i.e. a deteriorative process. On the other side, it can be observed that, through the increase of vehicle numbers, the delay of all ACs increase at approximately the same pace and also maintain the spacing with each other just like the previous two vehicle group merge, which proves the effectiveness of the EDCA mechanism and the relatively independent behavior of each AC in VANET.

Besides the delay in the dynamic environment, Figure 7-14 discloses a more critical issue in practical application, which is a hidden node problem that is rarely mentioned in WLAN nowadays, due to the successful CTS/RTS mechanism. It has never been brought out or found in previous scenarios because they are generally set in either a neglectable dimension or a logical subnet, in order to better study other factors impacting on VANET. However, in scenario 5, we found that there are always two throughput peaks happening at approximately 97s and 137s for each AC at testing node 01. After comparing to previous scenarios, I conclude that such a phenomenon is due to a hidden node issue, as there is no CTS/RTS mechanism in the broadcast mode. Apparently, vehicles in previous scenarios contend media with each other either in a logical subnet or an extreme dimension, in order to better study other changeable factors, thus never experiencing the hidden node problem.

However, in practical application, we need to divide collisions into two types: media contention collision and hidden node collision, which are combined in order to degrade VANET performance. In scenario-4, the packet received per second keeps increasing unless the loss rate reaches nearly 100%, although adding a vehicle number results in a higher collision rate. Concerning scenario-5, every node joining the effective communication coverage of testing node 01 will arouse a higher rate of both kinds of collision, which at some stage will overwhelm the impact of adding ACs. Simply put, even though more packets have been transmitted every second, the collision rate increases much faster and results in fewer packets being successfully received. Figure 7-15 provides the procedure of a vehicle group merge from the view of testing node 01.

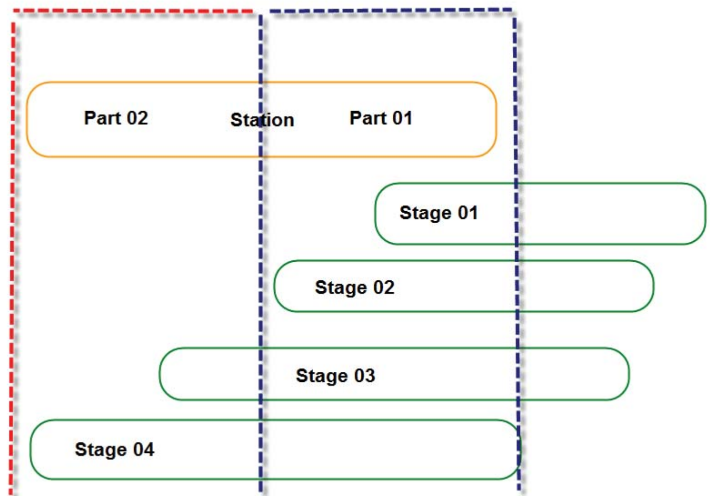

Figure 7-15 Vehicle Group Merge Procedure

In fact, the mechanism concerning dimension is very complex, although the above diagram looks simple. I will try my best to explain it by using AC 03 as an example. In our scenario, it shows one peak happening at stage 03. Firstly, from the view of testing node 01, we divide its effective communication coverage into two parts (01 and 02), whereby there is no hidden node collision within the same part due to pre-defined 1 Km coverage. When two vehicle groups start to merge with each other from stage 01 to 02, the overall packet transmission rate in part 01 increases, while the rate in part 02 remains the same, according to the conclusion from scenario-4 and the nature of a non-saturated network. Thus, at these stages, even with the number of hidden node collisions, testing node 01 can still receive more packets within a given time. Simply put, vehicles in part 01 outnumber its counterparts of 02. However, when vehicle group 02 pierces the middle line of group 01, where testing node 01 is located, the vehicle number in part 02 will increase, while the number in 01 does not change. At that time, a collision due to hidden node increases is due to more vehicles being fed into part 02, which act as antagonists against their counterparts in part 01. However, at the initial stage after piercing, a higher packet transmission rate may still be able to offset the impact of a greater overall collision rate; however, it loses its domination at a certain point in time.

7.3.3 Analysis of Testing Node 00/02

Meanwhile, it is necessary to understand that there are many factors contributing to the rate of hidden node collisions, including transmission coverage, length of vehicle fleet, packet generation frequency and vehicle location in group. For instance, we can predict that such a two-peak phenomenon dwindles when a vehicle is located further from the middle line of the group, thus indicating that there is only one peak at two edges of group 01, which is proved in Figure 7-16.

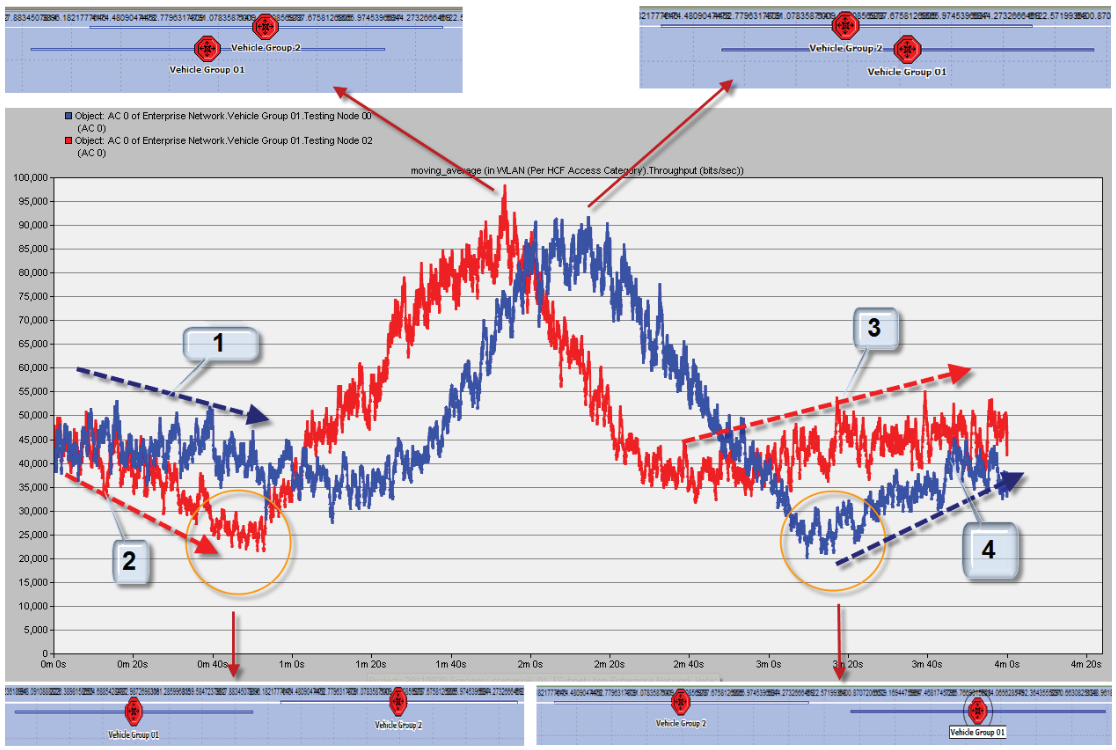

Figure 7-16 Throughput peaks of AC 3 at Testing Nodes 00 and 02

Analysis: From the above chart, we notice that, unlike Figure 7-13, there is only one highest peak and one lowest bottom for testing nodes at two edges of the vehicle group. The performance of throughput for each one turns out to be asymmetrical. For instance, throughput of 00 reaches its lowest value at a time point of around 3m17s, and experiences its second lowest bottom at 1m10s, as circled in orange on the chart. Meanwhile, there are symmetrical peaks and dips of testing nodes 00 and 02, which also show similarities at other points.

In order to explain and prove these statements and assumptions, it is necessary to further illustrate all eleven stages of vehicle group mergence in Figure 7-17.

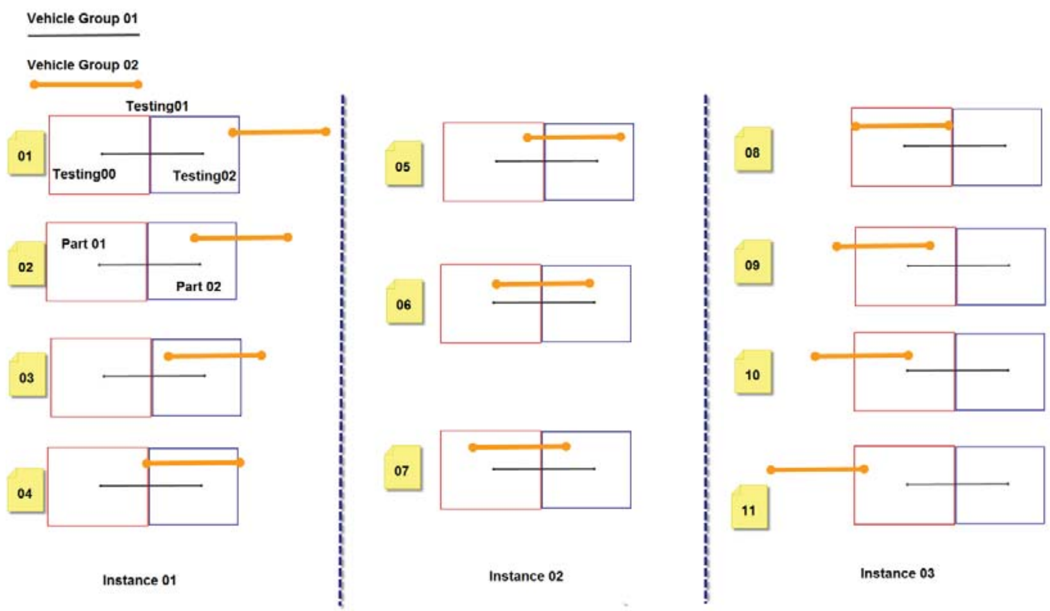

Figure 7-17 Eleven Stages of Vehicle Group Mergence

Parts 01 and 02 here are effective communication coverage for testing nodes 00 and 02, respectively. As we mentioned in previous analysis, due to the two types of collision existing in VANET, the packet receiving rate not only depends on how many vehicles are in coverage but also their locations. In our scenario, using testing node 02 as an example, part 02 can be sub-divided into left and right parts. Then, we define the vehicle number ration between left and right part as $\rho_{\mathrm{left/right}}$. Before the vehicle number changes in part 02, ρ is always 20/0 {Stage 01}, followed by 20/ (1-20) {Stage 01-02}, (21-40)/20 {Stage 02-04}, 40/(20-0) {Stage 04-06} and (40-20)/0 {Stage 06-08}. Thus, we can see that within these eight stages mostly affecting the performance of testing node 02, no pair can be considered symmetric. For instance, if ρ is 36/20 at Stage 03, we can never find 20/36 throughout all stages, due to the initial ρ being 20/0 in an asymmetric manner. That explains why throughput performance for 02 looks asymmetric and why there is only one highest peak and one lowest bottom happening at Stages 05 and 01, respectively.

Next, we study two less fluctuated trend lines of testing node 02, namely 2 and 3 marked by a dashed arrow line in Figure 7-16. Concerning the first trend, it happens when two vehicles get close to each other until a little portion of vehicles in group 02 enters into effective coverage of testing node 02 (Stage 01). Meanwhile, trend line 3 comes under an opposite situation when vehicles of group 02 are further away from the coverage (Stage 09). Most of the time, there are no vehicle number changes within part 02 throughout these two trend lines, which indicates that such a phenomenon is mainly due to the impact of vehicles outside of the testing node 02 effective coverage. According to the conclusion of scenario-2, packets transmitted by vehicles located more than 1 Km, even if they can be harder decoded or sensed along with distance, will arouse a higher probability of a sensed busy period, thus reducing the throughput of testing node 02. A similar mechanism causes trend line 03, where out of coverage vehicles, to gradually have a lower negative impact on part 02. However, the reason that the lowest bottom is found on trend line 2 rather than 3 is because there are still hidden node collisions on time periods of trend lines 2 and 3. Also, the former instance turned out to represent a much more balanced pattern on two sides of part 02, namely lower ρ. Thus, hidden node collisions in trend line 02 will be higher than their counterparts of 03.

By reviewing Figure 7-17 again, we notice that there are symmetric patterns in this chart, which are based on middle Stage 06. For instance, Stage 02/10 can be considered as a 180^0 rotated pair. However, it requests us to change the view from testing node 02 to 00; otherwise, it cannot be considered as equal. Combining what we studied previously, we can conclude that every stage experience by testing node 02 will not repeat itself but will still be a counterpart of 00 in a reversed sequence, due to the location and relative movement of these two vehicle groups. Therefore, we predict that their throughput patterns need to be both rotated and shifted based on a time axle, which is proved in Figure 7-18.

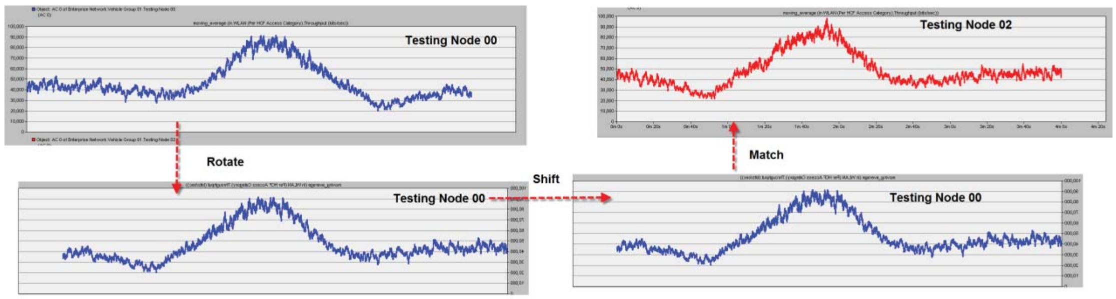

Figure 7-18 Rotation and Shift of Testing Node 02 Throughput Diagram

From what is stated above, it reveals that throughout the procedure of an approaching vehicle group at any given time point, every vehicle in the group will contribute a different performance. Their delays will all be presented in a bell-shaped curve but will have space between one another due to location difference. On the other side, the performance of throughput turns out to be more complex, whereby every node evolves based on the counterpart in the middle of the vehicle group. Figures 7-19 and 7-20 demonstrate the evolution.

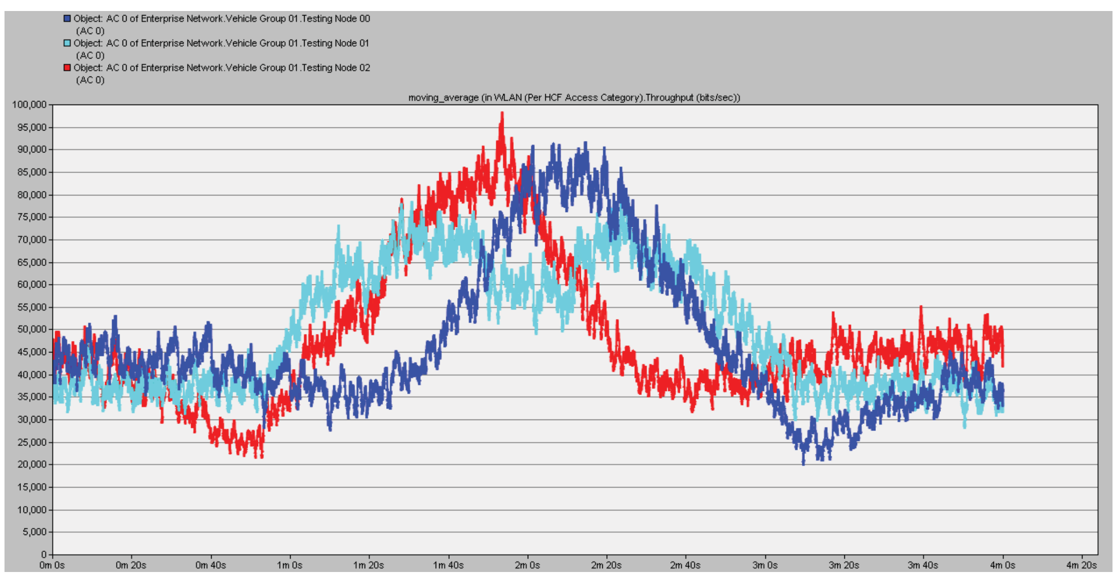

Figure 7-19 Throughput of Testing Node 00/01/02 in One Chart

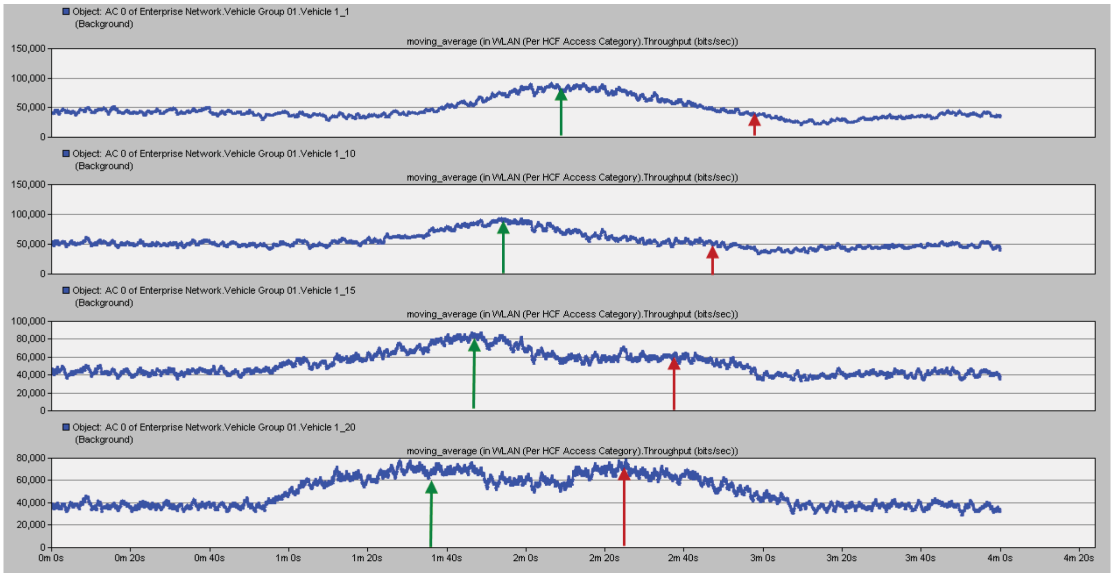

Figure 7-20 Reception Throughput of Vehicle 01/10/15/20

From Figure 7-20, we see how this two peak phenomenon evolves from edge to middle of the vehicle group. It seems that when the distance between node and group middle line becomes shorter, the side containing the lowest bottom will gradually ramp up, which will push the existing peak (green arrow indicated) backwards and will make itself approach the middle line of the time axle (red arrow indicated) until the two peaks equally locate at each side of it.

Chapter 8 Conclusion and Future Work

8.1 Conclusion

In previous chapters, we simulated different scenarios for a CCH performance study under 801.11p. The results indicate that various factors cooperating with each other will impact on the performance duo of a dynamically changing communication environment and can be summarised as follows:

1 According to [66], the latencies for pre-crash and collision risk warning should not be more than 50ms and 100ms, respectively. The results of all instances in our simulations meet that requirement very well. For example, under instance-5 of scenario-4, whereby 133 vehicles start to contend media within 2 ms and each AC carries 1400 bits/packet, the delay of AC 3 only reaches 7.25 ms, which indicates that 802.11p is capable enough of meeting the latency requirement for road safety applications.

2 EDCA is an effective protocol to assign distinguishing media access priorities to different types of ACs throughout our simulations. Especially under the situation where media resources are heavily occupied, the mechanism tends to sacrifice the transmission opportunity of ACs starting from the lowest priority in order to maintain the operation of ACs with higher priorities.

3 Under the CCH broadcast mode, the packet collision caused by media contention might be an issue. In general, the performance of AC with higher priority is more sensitive to the number of vehicles transmitting within a guard interval and packet size. In instance-4 of our simulation, where only ten vehicles carrying AC 3 data stream at 48 bits/packet, the collision rate can reach 21.55% and can seem too high to be feasible, when two factors previously mentioned further increase.

4 The VANET adopted 802.11p protocol might be under risk of a broadcast storm and is not very capable of dealing with an occasionally heavy load of higher priority AC streams, since it eliminates the TXOP mechanism and evolves from the IEEE 802.11 family, which are all for unicast most of the time and are in shortage of an effective mechanism for broadcasting or multicasting. Meanwhile, in these situations, not only

the CCH interval will be affected but also its SCH counterpart, due to a high collision rate and latency of AC 0, which is supposed to provide information for WBSS association.

5 Throughout the process of vehicle fleet mergence, the performance of each vehicle will fluctuate significantly, which also distinguishes each other according to the position of its fleet, due to the combined effects of communication coverage (including effective and edge) as well as collision, due to hidden nodes. The latter one is inevitable under the CCH broadcast mode since there is no RTS/CTS mechanism.

8.2 Future Work

In this thesis, we studied the performance of CCH in VANET in various situations with the aid of OPNET. There are several recommendations we would like to provide for further study of IEEE 802.11p, as follows:

1 It is hard to predict when an immediate 802.11p module will be available on OPNET. Thus, within a relatively long-term period, the performance study still needs to rely on the modification of current available WLAN modules. To be specific, the objective of a wireless station needs to be to contain more than one wlan_mac_intf in order to support multiple ACs and carry out and facilitate an internal contention mechanism based on a single wireless_lan_mac.

2 Furthermore, although SCH will not directly be involved in road safety applications, its performance might still need to be reviewed based on two reasons. Firstly, communication on SCH is not an isolated procedure from its counterpart of CCH but completely depends on it due to the reasons of AC 0 mentioned in previous conclusions. Secondly, a STA is only able to estimate the communication conditions during an SCH interval for the purpose of adjusting its transmission power, data rate, packet size, etc., since the broadcast mode on CCH is a one-way transmission mechanism and no feedback can be obtained during that period. In short, communications on CCH and SCH are dependable on each other in some cases and

cooperate together to intelligently adjust themselves in order to enhance the overall performance.

3 The impacts of geographic terrains, multipath propagation and fading on VANET performance might need to be taken into consideration, as well as dynamically changing vehicle topology, through the development of an exclusive propagation modelling module for IEEE 802.11p. Current modelling in OPNET, like HATA, Longley Rice, and Walfisch-Ikegami, cannot all be applied on the 5 GHz band directly.

4 The current 802.11p standard might demand further enhancement to address two main prominent issues: broadcast storm and packet collision. The solution for the former could be multi-hop forwarding or restoration of TXOP. The latter seems more difficult to deal with and we advise researchers to consider modifying PHY of DSRC by adding the latest multiple-input and multiple-output (MIMO) technology, together with frequency hopping for some ACs with relatively high priorities.

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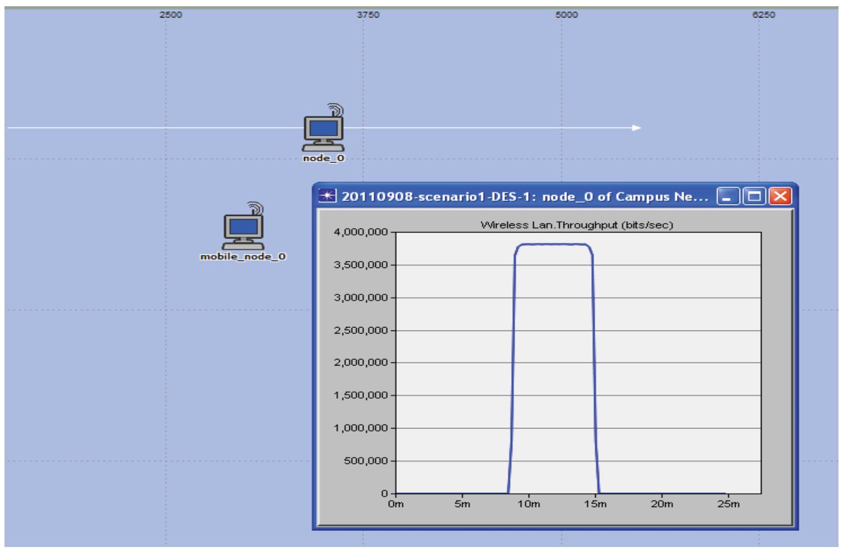
Appendix

Transmission Power Estimation

Objects: One fixed node, one mobile node, 4 Km trajectory

Parameter Setting: 801.11p, 10 Km/h for mobile node (very low speed), 6 Mbps, 0.005 W for transmission power



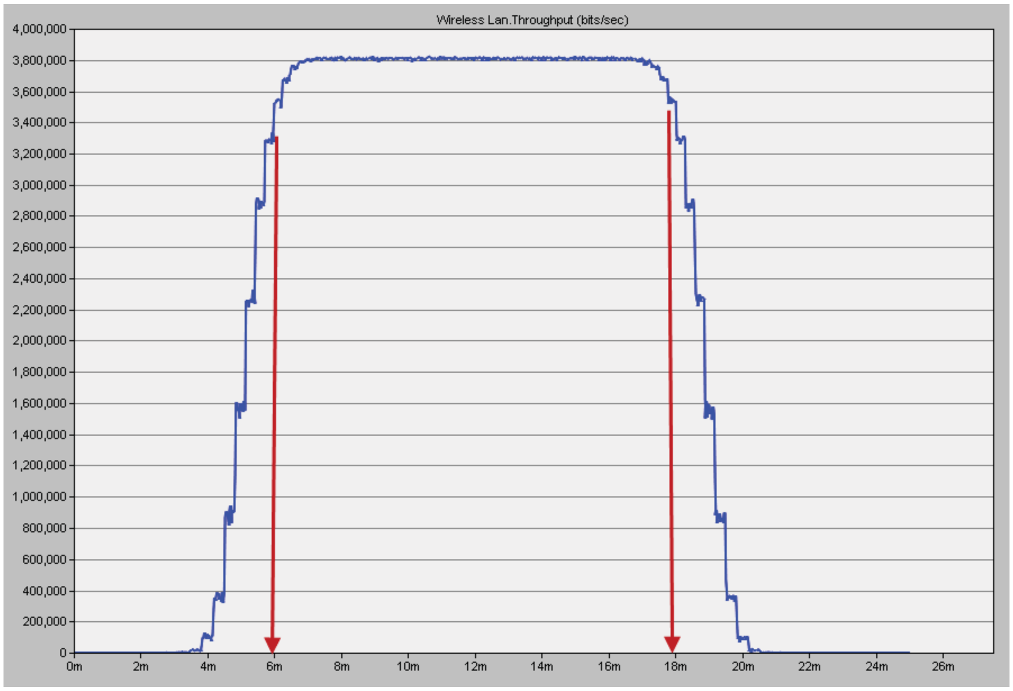
Some Results Hidden	
time (sec)	**Throughput (bits/s)**
529.5	0
531	0
532.5	0
534	0
535.5	1478937.108
537	4651494.892
898.5	4663967.944
900	4654091.944
901.5	4654443.944
903	1474515.05

The above results only indicate a 364.5 second stable transmission and show that 0.005 W is not enough for 1 Km coverage, as it has to last 720 seconds (1 Km at each side of fixed node). According to the free space loss formula, we define N in dBm at a critical point (at 537 seconds). Thus,

N= 7 – {32.45+ 20*lg5885+20*lg(2-537*2.777777/1000)}   (7 dBm here equals to 0.005W)

Thus, N≈-95 dBm. In the case of there being 1 Km coverage, we can get transmission power to be 12.87702108 dBm, which is equal to 0.01939555W.

The result actually perfectly matches our expectation, as a 12 minute stable communication can be observed after applying the above transmission power.



Simulation Results

Table of Average Delay under three same kind ACs only of Instance 1

Access Category	Packet Size (bits)					
	48	96	192	384	768	1400
	Average Delay (ms)					
AC 3	0.2073	0.33533	0.517036	0.96221	1.85351	3.3177
AC 2	0.2162	0.3442	0.5249	0.9711	1.8635	3.3345
AC 1	0.2611	0.3777	0.5908	1.067	2.0195	3.5897
AC 0	0.3041	0.4146	0.6625	1.1586	2.1507	3.7862

Tables of Sub-Instance for Study of Packet Size Impact

sub-instance 0	Packet Size of AC 0					
Access Category	48	96	192	384	768	1400
	Average Delay (ms)					
AC 3	1.0093	0.9964	0.9919	1.019	1.2534	1.6993
AC 2	1.2637	1.2782	1.2526	1.2664	1.2691	1.2751
AC 1	3.2003	3.2205	3.2169	3.2642	3.3401	3.5314
AC 0	3.3863	3.5267	3.7474	4.223	5.312	7.1741

sub-instance 0	Packet Size of AC 1					
Access Category	48	96	192	384	768	1400
	Average Delay (ms)					
AC 3	0.9895	0.9853	0.986	1.0192	1.0844	1.6827
AC 2	1.2357	1.2455	1.2502	1.2662	1.2939	1.3601
AC 1	2.4634	2.5679	2.7959	3.2568	4.2265	5.8656
AC 0	3.1017	3.2537	3.5753	4.2077	5.8533	8.2417

sub-instance 0	Packet Size of AC 2					
Access Category	48	96	192	384	768	1400
	Average Delay (ms)					
AC 3	0.75	0.7501	0.809	1.0205	1.3572	2.1076
AC 2	0.6057	0.6922	0.9058	1.2714	2.1689	3.6666
AC 1	2.3965	2.3746	2.6681	3.266	4.6692	7.3751
AC 0	3.3079	3.3232	3.6358	4.234	5.9344	8.5882

sub-instance 0	**Packet Size of AC 3**					
Access Category	**48**	**96**	**192**	**384**	**768**	**1400**
	Average Delay (ms)					
AC 3	0.4733	0.5504	0.7011	1.02	1.7161	2.843
AC 2	1.0595	1.0792	1.1371	1.2756	1.5824	2.111
AC 1	2.5956	2.6927	2.8584	3.2059	4.1028	5.8219
AC 0	3.6067	3.6813	3.8686	4.2196	5.3499	8.0651

Vehicle Number Impact on VANET Performance under a single type of AC.

Only one AC 0 for each Vehicle												
Vehicle Number	Packet Size (bits)											
	48		96		192		384		768		1400	
	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s
10	0.435	87.81833	0.632	84.34219	1.071	84.24333	1.982	76.76667	4.365	71.71667	8.06	68.66
20	0.847	135.72	1.219	127.8767	1.988	113.9567	3.943	98.43984	7.638	90.29	13.613	86.60333
30	1.103	164.94	1.577	154.5833	2.719	132.4133	5.548	112.09	10.451	100.58	17.531	96.51
40	1.31	186.885	1.469	171.51	2.873	147.9733	6.139	124.0633	11.689	107.36	20.756	103.3533
50	1.488	219.95	1.636	188.1833	3.828	158.8567	6.785	131.7033	13.403	114.6467	23.112	109.2567
60	1.507	255.2167	1.987	194.2033	4.412	162.42	7.788	136.0533	15.099	119.6267	25.413	113.65
70	1.688	263.7917	2.335	211.8233	4.705	185.06	8.603	148.1167	15.76	122.8433	27.23	117.3967
80	1.97	266.3417	2.903	243.53	4.858	198.4167	9.01	184.025	16.397	125.8167	28.027	120.0833
90	1.94	276.6333	2.643	254.6833	5.046	204.1	9.375	188.0833	17.044	132.9083	29.341	124.2833
100	2.103	277.1083	2.926	252.1833	5.414	202.775	9.952	188.675	17.931	149.8333	30.636	145.75

Only one AC 3 for each Vehicle												
Vehicle Number	Packet Size (bits)											
	48		96		192		384		768		1400	
	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s	Average Delay (ms)	packet/s
10	0.19709	78.44333	0.333	67.86	0.52554	59.675	0.981036	48.0288	1.9	41.854	4.30656	33.975
20	0.22412	105.2733	0.3408	91.18667	0.643358	72.50833	1.3227	51.26667	2.3211	34.50345	4.91937	28.11667
30	0.22432	144.2367	0.361059	120.02	0.705417	87.4166	1.31056	60.65	2.54259	37.94167	4.85725	28.1333
40	0.23305	173.85	0.36632	132.7833	0.63767	97.49167	1.248785	68.3166	2.29944	45.10833	4.867532	32.54167
50	0.23147	218.4733	0.39406	158.0933	0.67429	112.55	1.27073	77.175	2.6323	46.358833	5.0058	32.9333
60	0.2574	227.27	0.40999	169.7	0.682029	120.8833	1.41107	79.775	2.80543	45.65	5.41901	33.14991
70	0.27872	236.02	0.42957	174.77	0.6469	128.0917	1.257	85.34167	2.8278	50.7333	5.70286	34.36718
80	0.283	222.0417	0.43028	169.5083	0.6777	123.2333	1.34949	83.1167	2.88459	48.80833	5.75761	33.75359
90	0.311	242.3417	0.44283	174.2833	0.73684535	131.4	1.40357	91.05	2.92848	52.29167	5.73357	37.075
100	0.322	242.3833	0.45835	170.175	0.789712	137.4917	1.46215	97.625	3.2702	58.26667	6.904844	46.48333

VANET Performance under Multiple-AC Types

All Under 133 Vehicles Instance, Average Data

Access Category	48: Delay (ms)	48: Receiver Throughput (bits/s)	48: Overall Transmitter Throughput (bits/s)	48: Bit Loss Rate	96: Delay (ms)	96: Receiver Throughput (bits/s)	96: Overall Transmitter Throughput (bits/s)	96: Bit Loss Rate	192: Delay (ms)	192: Receiver Throughput (bits/s)	192: Overall Transmitter Throughput (bits/s)	192: Bit Loss Rate
AC 0	15.95292	49174.1044	510661.48	90.371%	19.232298	101403.476	766231.88	86.77%	25.26693	199526.355	1276756.709	84.37%
AC 1	8.86453093	25448.468		95.017%	11.042832	48313.9011		93.69%	13.975754	88946.8525		93.03%
AC 2	1.95762164	28115.1811		94.494%	2.9972386	41561.628		94.58%	4.4361218	60647.612		95.25%
AC 3	0.55959145	64268.8098		87.415%	0.86452228	92342.961		87.95%	1.3123944	117199.143		90.82%

Packet Size (bits)

Access Category	384: Delay (ms)	384: Receiver Throughput (bits/s)	384: Overall Transmitter Throughput (bits/s)	384: Bit Loss Rate	768: Delay (ms)	768: Receiver Throughput (bits/s)	768: Overall Transmitter Throughput (bits/s)	768: Bit Loss Rate	1400: Delay (ms)	1400: Receiver Throughput (bits/s)	1400: Overall Transmitter Throughput (bits/s)	1400: Bit Loss Rate
AC 0	37.996949	394089.429	2300622.362	82.87%	64.527591	737199.715	4344109.806	83.03%	not applicable			
AC 1	19.691364	175943.53		92.35%	32.134314	340401.428		92.16%	47.62549	578221.127	7710376.282	92.50%
AC 2	6.5114472	97018.42		95.78%	10.2290551	182478.624		95.80%	19.789639	207503.735		97.31%
AC 3	2.21315012	137071.54		94.04%	4.5360998	134862.148		96.90%	7.2537357	176406.445		97.71%