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# Ordonnancement et qualité de service dans les réseaux sans fil véhiculaires

Lusheng Miao

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UNIVERSITÉ PARIS-EST

ÉCOLE DOCTORALE : MSTIC

**Thèse de doctorat**

**Télécommunication**

**Lusheng Miao**

**Ordonnancement et qualité de services dans les réseaux sans fil véhiculaire**  
**Scheduling and Quality of Service enhancement in Wireless Vehicular ad-hoc Networks**

*Thèse dirigée par*  
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Soutenue le 16 Décembre 2014

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**SCHEDULING AND QoS ENHANCEMENT IN WIRELESS  
VEHICULAR AD-HOC NETWORKS**

**by**

**Lusheng Miao**

Submitted in partial fulfilment of the requirement for the degree

**DOCTOR TECHNOLOGIAE: ELECTRICAL ENGINEERING**

**DOCTOR OF PHILOSOPHY: COMPUTER SCIENCE**

in the

Department of Electrical Engineering

French South African Institute of Technology (F'SATI)

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May 2014



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Lusheng Miao

DATE

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# **Dedication**

This study is dedicated to my wife Caiyan Hu and my son Yi Miao for their unconditional support and love and to my parents and brother for their support and encouragement.





# Acknowledgments

I would like to express my sincere gratitude and appreciation to: My supervisor, Prof. Karim Djouani and Co-supervisors, Prof. Barend Jacobus Van Wyk and Prof. Yskandar Hamam, for their advice, comment and guidance.

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# Abstract

Vehicular ad-hoc Networks (VANETs) are becoming more and more popular as a means to increase traffic safety and comfort. VANETs possess some particular characteristics due to the high speeds and mobility of vehicles, such as rapid changes of topology, potentially large-scale, variable network density and so on. These characteristics have important implications for the design of MAC protocol in VANETs. Attention is increasingly being paid to the 802.11p standard as an important part of the WAVE protocol in VANETs. However the QoS of 802.11p standard is not yet able to meet the realistic requirements of the vehicular communication networks. Three sub-problems are identified in this study: the (i) CCH and SCHs duty cycle problem, (ii) QoS analysis problem and (iii) Multichannel MAC protocol designing problem.

Focussing on these problems, three approaches are undertaken in this study: (i) To propose a duty cycle adaptive MAC protocol in which the duty cycle of CCH and SCH will be adapted based on the realtime network traffic; (ii) To propose a model to analyse the QoS in VANETs with various SCH interval settings; (iii) To propose a scheduling and QoS enhancement multi-channel MAC protocol in VANETs.

All the proposed algorithms are implemented and validated in discrete event simulator. The simulation results demonstrate that the important QoS metrics such as the reliability, throughput, successful throughput, network capacity and channel utilisation are improved by the proposed algorithms in this project.



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# Glossary

## Acronyms / Abbreviations

*AC* Access Class

*AIFS* Arbitration Inter-Frame Space

*AIFSN* Arbitration Inter-Frame Space Number

*AODV* Ad hoc On-Demand Distance Vector Routing

*BER* Bit Error Rate

*BGP* Border Gateway Protocol

*BPSK* Binary Phase Shift Keying

*BSM* Basic Safety Message

*CCH* Control Channel

*CEA* Centralised Enhancement Algorithm

*CRaSCH* Cooperative Reservation of SCH

*CSMA* Carrier Sense Multiple Access

*CSMA/CA* Carrier Sense Multiple Access with Collision Avoidance

*CW* Contention Window

*DCF* Distributed Coordination Function

*DEA* Distributed Enhancement Algorithm

*DIFS* DCF Interframe Space

*DSR* Dynamic Source Routing Protocol

*DSRC* Dedicated Short Range Communications

## Glossary

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*DYMO* Dynamic MANET On-demand

*EDCA* Enhanced Distributed Channel Access

*EIRP* Equivalent Isotropically Radiated Power

*FER* Frame Error Rate

*FER* Frame Error Rate

*FPGA* Field Programmable Gate Array

*HCF* Hybrid Coordination Function

*ICI* Inter Carrier Interferences

*ITS* Intelligent Transportation Systems

*ITS – RS* Intelligent Transportation Systems Radio Service

*IVC* Inter-Vehicle Communication

*LANs* Local Area Networks

*LDP* Label Distribution Protocol

*LoS* Line of Sight

*MAC* Medium Access Control

*MANET* Mobile Ad hoc network

*MIMO – STBC* Multi-Input Multi-Output Space-Time Block Coding

*MPLS* Multi-Protocol Label Switching

*ns – 2* Network Simulator-2

*OBU* On Board Unit

*OFDM* Orthogonal Frequency Division Modulation

*OLSR* Optimized Link State Routing

*OSPF* Open Shortest Path First

*PAR* Project Authorisation Request

*PER* Packet Error Rate

<i>PHY</i>	Physical layer
<i>PPP</i>	Point to Point Protocol
<i>QAM</i>	Quadrature Amplitude Modulation
<i>QoS</i>	Quality of Service
<i>QPSK</i>	Quadrature Phase Shift Keying
<i>R2V</i>	Roadside-to-Vehicle
<i>RIP</i>	Routing Information Protocol
<i>RSTP</i>	Rapid Spanning Tree Protocol
<i>RSU</i>	Road Side Unit
<i>RSVP – TE</i>	Resource ReSerVation Protocol-Traffic Engineering
<i>SCH</i>	Service Channel
<i>SCTP</i>	Stream Control Transmission Protocol
<i>SIFS</i>	Short Inter-Frame Space
<i>SISO</i>	Single Input Single output
<i>SNR</i>	Signal Noise Ratio
<i>STDMA</i>	Self-organizing Time Division Multiple Access
<i>TCP</i>	Transmission Control Protocol
<i>TDMA</i>	Time Division Multiple Access
<i>TraCI</i>	Traffic Control Interface
<i>UDP</i>	User Datagram Protocol
<i>V2I</i>	Vehicle-to-Infrastructure
<i>V2V</i>	Vehicle-to-Vehicle
<i>V2X</i>	vehicle-to-anything
<i>VANETs</i>	Vehicular ad-hoc Networks
<i>VCAS</i>	Vehicular Channel Access Scheme



## **Glossary**

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*Veins* Vehicles in Network Simulation

*W – HCF* WAVE-based Hybrid Coordination Function

*W – UIM* WBSS User Initiation Mode

*WAVE* Wireless Access in a Vehicular Environment

*WBSS* WAVE Basic Service Set

*WIMAX* Worldwide Interoperability for Microwave Access

*WSA* WAVE Service Advertisement

*WSM* Wave Short Message

# Chapter 1

## Introduction

### 1.1 Introduction

Vehicular ad-hoc Networks (VANETs) have increasingly attracted attention owing to our society's transportation problems such as traffic congestion, traffic accidents, lack of mobility and accessibility and the like. Over the last two decades, several technical groups such as the IEEE 1609 Working Group [160], the IEEE 802.11p Task Group [12], the ISO TC204 Working Group 16 [ISO] and the ETSI [ETS] ITS Technical Committee were created in an attempt to solve the said problems. From that perspective, three major categories of applications were targeted: (i) road safety, (ii) traffic efficiency, and (iii) value added applications. VANETs constitute the cornerstone of the envisioned Intelligent Transportation Systems (ITS). By enabling vehicles to communicate with each other via Inter-Vehicle Communication (IVC), alternatively known as Vehicle-to-Vehicle (V2V), as well as with roadside base stations via Roadside-to-Vehicle Communication (RVC), also known as Vehicle-to-Infrastructure (V2I), VANETs will contribute to safer and more efficient road system by providing timely information to drivers and the authorities concerned.

VANETs present a challenging environment for protocol and application design due to their low latency and high data rate requirements in a high mobility environment. The IEEE 1609 working group has defined the first version of the protocol stack IEEE 802.11p/1609.x protocol families [61], also known as WAVE (Wireless Access in a Vehicular Environment). The WAVE protocols are designed for the 5.850-5.925 GHz band, the Dedicated Short Range Communications (DSRC) spectrum band in the United States (US), known as Intelligent Transportation Systems Radio Service (ITS-RS). This 75 MHz band is divided into one central Control Channel (CCH) and six Service Channels (SCH) as depicted in Fig. 1.1. An overview of the WAVE protocol families is illustrated in Fig. 1.2. The IEEE 802.11p standard [12] defines the Physical (PHY) and Medium Access Control (MAC) layers based on previous standards for Wireless

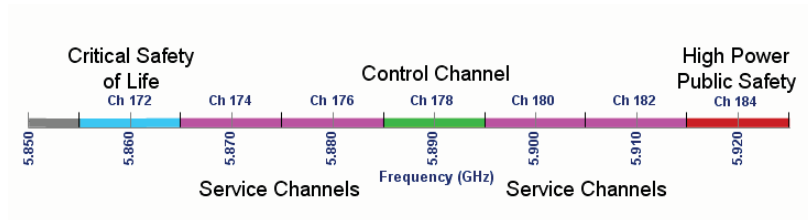


Fig. 1.1 The set of channels defined in the WAVE trial standard [42]

LANs (Local Area Networks). The IEEE 802.11p uses the Enhanced Distributed Channel Access (EDCA) MAC sub-layer protocol designed based on the IEEE 802.11e with some modifications, while the physical layer is OFDM (Orthogonal Frequency Division Modulation) as used in IEEE 802.11a.

## 1.2 Problem Statement

VANETs are becoming more and more popular as a means for increasing traffic safety and comfort. VANETs possess some particular characteristics due to the high speeds of vehicles such as encountering rapid changes of topology, potentially large-scale, variable network density and so on [38]. These characteristics have important implications for the design of MAC protocol in VANETs. The 802.11p standard is increasingly attracting attention as an important aspect of the WAVE protocol in VANETs. However the 802.11p standard is still a new and draft standard and the important metrics of QoS (Quality of Service), such as collision, reliability, throughput and delays, still need to be analysed and improved in order to meet the requirements of the realistic vehicular communication networks.

To improve the QoS in VANETs, three sub-problems were identified for this study:

1. While the 802.11p standard sets a fixed 50ms duty cycle for CCH and SCH, but the 50ms interval for CCH would be not enough for delivering the safety related

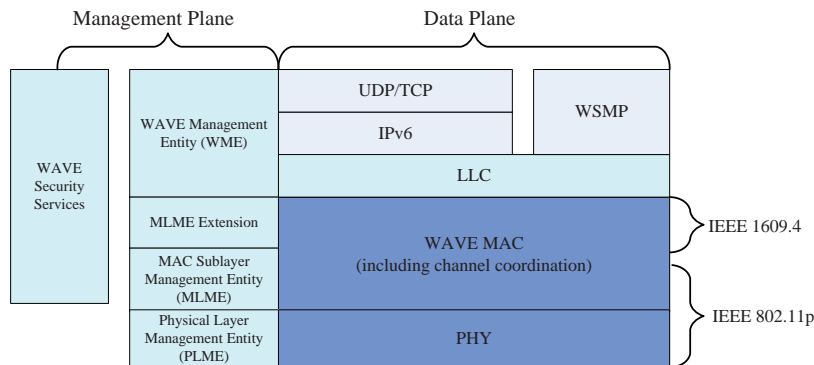


Fig. 1.2 The WAVE protocol suit [14]

message when there is the vehicle density. On the other hand, the 50ms interval for CCH could be wasted when the vehicle density is quite low.

2. The design of a an actual VANET needs to consider the network cost while meeting the service requirement. More transceivers equipped with a Road Side Unit (RSU) or an On Board Unit (OBU) can offer more services; consequently the network will be more expensive. Thus, a comprehensive analysis of QoS for different VANETs, equipped with various numbers of transceivers, needs to be done.
3. One CCH and six SCHs are assigned to WAVE, hence the efficient scheduling algorithm is a key requirement to access the multi-channel and improve the QoS in VANETs.

Based on the above-mentioned sub-problems, the aim of this study is described as follows:

1. To propose a duty cycle adaptive MAC protocol in which the duty cycle of CCH and SCH will be adapted based on the real time network traffic.
2. To propose a model to analyse the QoS for different VANETs with various SCH interval settings.
3. To propose a scheduling and QoS enhancement multi-channel MAC protocol in VANETs.

## 1.3 Hypotheses

1. An extension of the duty cycle of CCH in an environment where the vehicle density is high, will improve the performance of the safety related message, due to the extended CCH interval. On the other hand, decreasing the duty cycle of CCH in an environment where the vehicle density is quite low, consequently, the SCH interval will be extended and the non-safety related services will be improved, due to the extended SCH interval.
2. A comprehensive and accurate QoS analytical model would be very useful to the network designer, as well as the analysis of the network QoS.
3. An efficient multi-channel MAC protocol carried out for VANETs, in which the six SCHs can be efficiently accessed, would significantly improve the QoS of VANETs.

### 1.4 Importance of this Study

As mentioned, the protocol design in VANETs is very challenging due to their low latency and high data rate requirements in a high mobility environment. Hence, the central metrics of QoS such as throughput, reliability and delays are critical to the design of protocol in VANETs. Therefore, this project focuses on the scheduling and QoS enhancement algorithms. The QoS analytical model and multi-channel MAC protocol were completed; this was significant for the development of the VANETs. The anticipated benefits of this study may be described as:

1. The duty cycle adaptive MAC protocol could improve the QoS of VANET in the situation where the OBU is equipped with only one transceiver.
2. The results obtained from this model is significant for the designing and evaluation of the vehicular network.
3. Due to the characteristics of VANETs, the requirements of high throughput and low latency are critical in VANETs. An efficient multi-channel MAC protocol is a vital requirement in order to offer efficient, fair and stable channel access using the limited channel resources.

### 1.5 Delimitations of the Study

This study has the following delimitations:

1. This study is based largely on the 802.11p standard while the other standards for VANETs are not considered.
2. The research is based on a simulated environment; the proposed algorithms are simulated and compared, in terms of a similar, assumed environment. A real experimental environment would be very expensive if the costs of different transceivers and vehicle densities are taken into consideration.
3. The Line of Sight (LoS) blocking problems, caused by trucks or buildings, are not considered in this study. The effect of LoS blocking in the real-world network is unpredictable.

### 1.6 Research Methodology

In this study, the following approach was taken:

1. Information was gathered by means of a literature survey so as to understand the current state of the research;
2. The above information was summarised and analysed in order to develop feasible research directions;
3. Based on the existing simulation model for VANETs, a simulation model according to the IEEE 802.11p and 1609.X specification was developed;
4. A performance evaluation of the IEEE 802.11p MAC on CCH was done;
5. A duty cycle adaptive algorithm for the network where each OBU is equipped with only one transceiver was explored;
6. A performance evaluation of the proposed algorithm, using a discrete event simulator, was done;
7. An evaluation model to analyse the QoS for different VANETs with various SCH interval settings was designed.
8. A scheduling and QoS enhancement multi-channel MAC protocol for VANETs, was explored;
9. A performance evaluation of the proposed multi-channel MAC protocol, using a discrete event simulator, was undertaken.

## 1.7 Overview of Chapters

This section offers a brief overview of the dissertation. The first chapter introduces the research, presents the research problem and defines the methodology that was used.

**Chapter 2** The relevant literature is described and discussed. Firstly, an overview of the 802.11p standard is described. Secondly, the existing evaluations and enhancements of the 802.11p standard are presented and discussed. Finally, the current situations and future research directions of the 802.11p standard are identified.

**Chapter 3** In this chapter, the simulation platforms, which are used to evaluate the performance of IEEE 802.11p and validate the proposed algorithms, are discussed.

**Chapter 4** In this chapter, the performance of 802.11p on CCH is evaluated along with various CCH intervals: firstly, a CCH/SCH cycle adaptive algorithm is proposed, and thereafter evaluated and discussed. A CCH adaptive algorithm is then proposed, in which the CCH interval is adjusted according to the number of contention vehicles.

## **Introduction**

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**Chapter 5** This chapter focuses on the SCH of 802.11p; firstly evaluating the performances of SCH with various SCH intervals and then a multi-SCH algorithm which considers two service channels is then proposed and discussed.

**Chapter 6** This chapter offers the conclusions of the study and a summary of the findings and recommendations is provided.

# Chapter 2

## Literature Review

### 2.1 Introduction

In this chapter, the related literature is reviewed and discussed. The aim of this study was to develop scheduling and QoS enhancement based on IEEE 802.11p protocol in wireless VANETs. The overview of 802.11p is presented first and then, secondly, the related evaluation and enhancement of 802.11p are discussed respectively. Thirdly, conclusions for current and future research directions of 802.11p are examined and discussed. Finally, the chapter concludes by identifying the research direction of this study.

### 2.2 Overview of 802.11p

The overview of the IEEE 802.11p standard presented here provides just the information required to make sense of the discussion. Further information may be found in [12] and [42].

In 2004, IEEE 802.11 standard group migrated to IEEE 802.11a, for low overhead operations in the DSRC spectrum. Within IEEE 802.11, the DSRC is known as IEEE 802.11p WAVE. The 802.11p is strictly a MAC and PHY level standard. All knowledge and complexities related to the DSRC channel plan and operational concept are taken care by the upper layer IEEE 1609 standards as shown in Fig. 1.2.

The IEEE 802.11p employs HCF (Hybrid Coordination Function) contention-based channel access EDCA as the MAC method, which is an enhanced version of the Distributed Coordination Function (DCF) of IEEE 802.11. EDCA uses Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CSMA/CA). The basic EDCA access method is depicted in Fig. 2.1. In an EDCA scheme, a node willing to transmit will sense the medium, and if the latter is idle for greater than or equal to an AIFS[AC] (Arbitration Inter-Frame Space [Access Class]) period, the node starts transmitting directly. If the channel becomes busy during the AIFS[AC], the node will defer the transmission



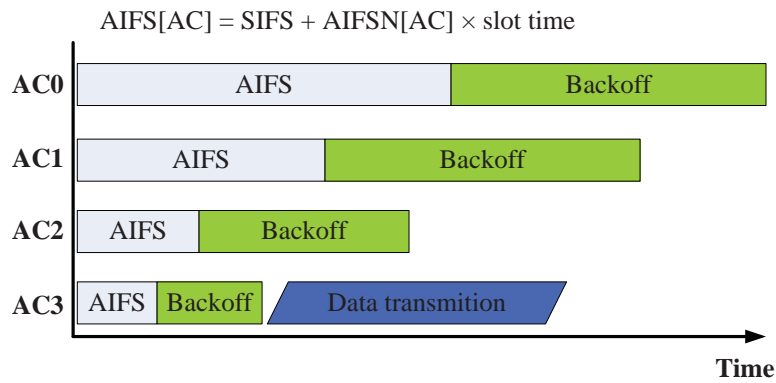


Fig. 2.1 A basic EDCA access scheme

by selecting a random Back-off time. The Back-off procedure in EDCA functions is as follows: (i) The node uniformly selects a Back-off time from the interval  $[0, \text{CW[AC]}]$  where the initial  $\text{CW[AC]}$  (Contention Window) value equals  $\text{CWmin[AC]}$ . (ii) The interval size will increase (double), if the subsequent transmission attempt fails, until the  $\text{CW[AC]}$  value equals  $\text{CWmax[AC]}$ . (iii) If no medium activity is indicated for the duration of a particular Back-off slot, then the Back-off procedure will decrement its Back-off time by a slot time. If the medium is determined to be busy at any time during a Back-off slot, then the Back-off procedure is suspended. The medium shall be determined to be idle for the duration of  $\text{AIFS[AC]}$ , before the Back-off procedure is allowed to resume. (iv) When reaching a Back-off value of 0, if the medium is sensed as being idle, the node will send immediately; If the medium becomes busy, the node will return to Back-off again. However, in this scenario, the value of the  $\text{CW[AC]}$  is left unchanged. In order to ensure that highly relevant safety messages can be exchanged timeously and reliably, even when operating in a dense vehicle scenario, the 802.11p MAC protocol accounts for the priority of the messages using different Access Classes (ACs). There are four available data traffic categories with different priorities: background traffic (BK or AC0), best effort traffic (BE or AC1), video traffic (VI or AC2) and voice traffic (VO or AC3). A set of distinct channel access parameters, including the Arbitration Inter-Frame Space Number (AIFSN) and CW, are selected for different ACs, as illustrated in Table 4.1. A basic EDCA access scheme is illustrated in Fig. 2.1, where SIFS refers to the Short Inter-Frame Space (SIFS). Each AC has a queue where messages are queued based on their priorities. If packets from different queues in the same station contend for the access, the message with higher priority will be accorded more opportunities to access the channel due to the smaller value of AIFSN and CW.

The physical layer of the 802.11p is a variation of the OFDM based IEEE 802.11a standard. The IEEE 802.11p PHY employs 64-subcarrier OFDM, of which 52 are used for actual transmission, consisting of 48 data subcarriers and 4 pilot subcarriers. The pilot signals are used for tracing the frequency offset and phase noise. In order to re-

Table 2.1 Parameter settings for different application categories in IEEE 802.11p [12].

AC	CW <sub>min</sub>	CW <sub>max</sub>	AIFSN
BK	15	1023	9
BE	15	1023	6
VI	7	15	3
VO	3	7	2

duce the effects of Doppler spread, the use of 10 MHz channels is adopted instead of the usual 20 MHz used by 802.11a. Consequently, all OFDM timing parameters are doubled (e.g. the guard interval, the OFDM symbol duration, etc.) and the data rates are halved (varying from 3 to 27 Mbps instead of 6 to 54 Mbps). The frequency is allocated at 5.850-5.925 GHz as displayed in Fig.1.1, which is divided into seven 10 MHz channels with a safety margin of 5 MHz at the lower end of the band. The centre channel CH178 is the control channel, which is reserved for system control and delivery of safety messages. The CH172 is retained for the critical safety of life service. The CH184 is reserved for the high power public safety service. The other four channels are used as service channels, where lower priority communication is conducted after negotiation on the control channel. According to the IEEE 1609.4 coordination scheme [14], as depicted in Fig. 2.2, the channel time is divided into synchronisation intervals with a fixed length of 100ms, consisting of 50ms (including 5ms guard interval) alternating CCH and SCH intervals. All vehicle transmissions stay in the control channel during the CCH period and switch to one of the service channels during the SCH interval. In addition, depending on the data rate that can be supported by channel conditions, four complex modulation methods: the Binary Phase Shift Keying (BPSK), the Quadrature Phase Shift Keying (QPSK), the 16 Quadrature Amplitude Modulation (16QAM), and the 64 Quadrature Amplitude Modulation (64QAM), are employed in the physical layer of the 802.11p. The default modulation parameters of PHY in 802.11p are illustrated in Table 2.2.

In WAVE, each vehicle is expected to join a WBSS (WAVE Basic Service Set), which

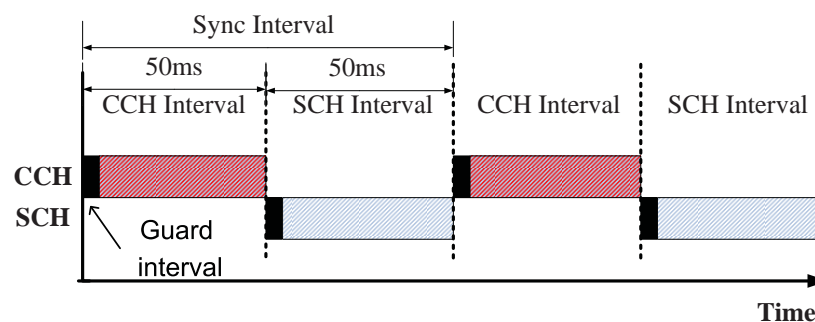


Fig. 2.2 Channel interval

Table 2.2 Parameter settings of PHY in IEEE 802.11p [10].

Modulation	Coding rate (R)	Data rate (Mb/s)
BPSK	1/2	3
BPSK	3/4	4.5
QPSK	1/2	6
QPSK	3/4	9
16-QAM	1/2	12
16-QAM	3/4	18
64-QAM	1/2	24
64-QAM	3/4	27

is a unique identifier for each communication zone. Vehicles must associate with just one WBSS at a time. Due to the high mobility of vehicles in VANETs, 802.11p simplifies the procedure to setup a WBSS without active scanning, association, and authentication procedures. To establish a WBSS, a provider periodically broadcasts the WAVE Service Advertisement (WSA) on the CCH. WSA contains the necessary information for the users to join the WBSS, such as the WBSS identifier, the availability of a service, the selected SCH, synchronisation timing information and the like. In the meantime, all the vehicles have to listen to the CCH during the CCH intervals. Thereafter, a user learns about available WBSSs and joins the WBSS, which provides the services in which the user is interested by simply switching to the advertised SCH during SCH intervals.

## 2.3 Evaluations of 802.11p

This section addresses the existing evaluations of this standard. These may be divided into three categories, according to the evaluation method used: (i) Analysis-based evaluation, (ii) Simulation-based evaluation and (iii) Test-based evaluation.

### 2.3.1 Analysis-based Evaluation

In analysis-based evaluation, only those analytical models that can be used to analyse the performance of the 802.11p protocol for the different network environments are presented.

Certain analytical evaluation models are proposed based on Markov chains in [37] [38] [39] [35] [20] [29]. In [37], an analytical model is proposed to compute the successful reception rate, collision probability and throughput of IEEE 802.11p within VANETs safety applications. The proposed model is based on a highway scenario in which the vehicles send status and emergency packets according to a Poisson distribution. In this

model, two one-dimensional Markov chains are proposed to calculate the transmission probabilities of both the status and emergency packets. Subsequently, the recommended maximum range  $R = 200m$  is derived from this model, which can be used to keep the delay as short as possible while achieving maximum throughput. In this model, two specified classes, AC3 and AC0, are considered for emergency broadcasts and status packets. However, in the Back-off process computation, an incorrect of DCF Interframe Space (DIFS) is used; it should be AIFS[AC]. In [38] and [39], a two-dimensional novel Markov chain analytical model for the 802.11p is proposed, which takes AIFS, CW for different ACs (AC0-AC3), while the internal collisions inside each station are accounted for. This analytical model is used to investigate the performance of the IEEE 802.11p MAC sub-layer in terms of throughput. However, it is analysed in a saturated scenario which does not model a realistic network. In [35], a discrete-time Markov chain based model is proposed for the EDCA MAC protocol, which considers the specific conditions of the control channel of a WAVE environment. The proposed model captures the fact that EDCA is able to establish priorities among the stations. The important metrics of QoS, such as throughput, losses, buffer occupancy and delays, are presented and analysed in this paper. However, the fact that the packet could return to Back-off many times is not considered. As a result, the delay obtained in [35] is not accurate and a little less than the real value. In [20], the authors propose an analytic model for safety message delivery when using the channel coordination mechanism defined in the 802.11p standard. The 802.11p standard is evaluated based on both heavy traffic and light traffic conditions. The evaluation results derived from the proposed model indicate that the 802.11p standard can satisfy the needed latency requirements (less than  $100ms$ ), but cannot satisfy the required reliability for the safety message delivery (greater than 99.9%). However, the heavy traffic conditions, which contain only 26 nodes, are not clearly explained in the paper; consequently, the evaluation results based on the heavy traffic conditions are questionable. In [29], an analytical framework to analyse the performance of periodic broadcasting on the CCH in 802.11p vehicular networks is proposed. The effects of different EDCA parameter sets on network performance are analysed under various traffic loads, error-prone channels, frame sizes and transmission data rates. The analytical modes are simulated using MATLAB. The results show that increasing the window size or decreasing the frame's size may increase the reliability of the transmission.

The effects of time allocations on CCH and SCH in IEEE 802.11p are analysed in [46] [47] and [20]. In [46], the effect is analysed while the CCH/SCH duty cycle is changing; the results obtained show that performance on CCH and SCH change significantly following the changing of the CCH/SCH duty cycle. It is demonstrated that CCH can accommodate around 80 users with best effort (AC1) and 80 users with background traffic (AC0) when the interval of CCH is set as  $9ms$ , and can accommodate 124 users for each of two background/best effort classes when the interval of CCH is set as  $45ms$ .

However, the effect is not analysed when the interval of CCH is greater than  $45ms$ . The authors continue their research in [47] where the trade-off between the CCH and SCH cycle is also analysed. The SCH service, which carries commercial infotainment applications, is a focus of this paper, as has been stated by the authors. In [20], it is indicated that the  $50ms$  CCH/SCH duty cycle value, as defined in the 802.11p standard, is a good choice, since increasing the CCH interval value more than  $50ms$  does not improve the performance on the CCH. However, as previously mentioned, the heavy traffic conditions which contain only 26 nodes are not lucidly explained in the paper and hence the evaluation results based on the heavy traffic conditions are considered questionable and unreliable.

In [16], a Packet Error Rate (PER) analytical model is proposed for 802.11p receivers to analyse the decoding process at the receiver. Most of the analytical models for 802.11p focus on the collision probability while the Frame Error Rate (FER) is neglected. The proposed FER analytical model describes the PER as the metric of a stochastic process depending on Signal-to-noise Ratio (SNR), line-rate and packet length, which is suitable for adoption by simulators, in order to give a more accurate simulation result.

In analysis-based evaluations, the MARKOV chain is the most popular metric to analyse the performance of the IEEE 802.11p. The CCH and SCH cycle is another well-known research topic which attracts a great deal of interest. In the analytical model, the packet size of safety messages, which could affect the evaluation accuracy, should be carefully considered. However, the packet size is set as 250, 500, and 1000 bytes in [37], 512 bytes in [38] and [35], 200 bytes in [20] and [39]. As defined in [11], the message size for the Basic Safety Message (BSM) Part I is 39 bytes and for the Part II, the Vehicle Safety Extension frame of the BSM which is less than 100 bytes. Hence, the packet size of the safety message should be 39 bytes for a simple BSM (only Part I) or 140 bytes for an extended BSM (Part I and Part II).

### 2.3.2 Simulation-based Evaluation

Certain simulation-based evaluations are proposed in [27] [36] [33] [49] to evaluate the 802.11p standard, based on different simulation models and scenarios. In [27], the authors present a model to analyse the characteristics and performance of C2C communication in urban environments. In the proposed model, it is assumed that the intervals of CCH and SCHs are equal and all the moving cars have information to transmit (only during SCH) in packets of 500 bytes. Subsequently, the model is simulated in a city scenario comprising an area of  $1km \times 1km$  and 100 blocks. The simulation results reveal that IEEE 802.11p technology is adequate, as long as the number of cars remains small ( $< 100$  cars in the simulation area). As the number of cars increases, (500, normal traffic flow), so the number of contention cases increases. With a dense traffic flow ( $>1000$  cars), the re-

sults are drastically degraded, even with the use of the EDCA mechanism. However, the simulation scenario does not consider the road safety applications during CCH, which are more critical and important in VANETs. Furthermore, the radio range, which is set as 250m, significantly affects the contention and the simulation. Hence, the number of contentions could be higher than the results obtained in this paper in a highway scenario, since the expected radio range for highway is up to 1000m [50]. In [36], the IEEE 1609 WAVE and 802.11p standards are evaluated under three distinct simulation scenarios. The first one is a flat open air environment with a number of static vehicles. The second is an urban environment corresponding to a region within Washington D.C.. The third scenario corresponds to a roughly linear segment of a long highway, with a number of road side units (RSUs) placed at varying intervals to generate transmission traffic towards the passing vehicles. Thereafter, three results are derived from the simulations: (i) control channel traffic, which can be successfully received even at a distance of 2.5km in an open air scenario with a 3Mbps data rate and 44.8dBm Equivalent Isotropically Radiated Power (EIRP); (ii) to ensure a moving vehicle can receive a steady data stream from the RSUs, the inter-RSU distance should fall in the range of 1000m-1500m; (iii) the delay on the control channel becomes longer than 100ms only when the total of the traffic offered approaches 1000 packets per second, which is too high for safety critical applications. Therefore this paper indicates that both WAVE and 802.11p appear to form a solid foundation for vehicular communication applications. In [33], the authors evaluate the IEEE 802.11p by considering collision probability, throughput and delay, by means of simulations and analysis. The simulation results indicate that the average value of end-to-end delay for AC3 is 1s for 300 nodes with a total offered traffic of 3000 packets per second. However, when the delay is longer than 100ms, the traffic threshold cannot be seen from the simulation results. Moreover, the delay for the scenario when the number of nodes is less than 150 is not presented well either. In [49], the 802.11p standard is evaluated based on the ns-2 simulator. This is derived from simulation results that the aggregate throughput, average delay, and packet loss are not affected by the vehicle speed, but are significantly affected by the vehicle density. When the vehicle density increases, the aggregate throughput, and packet loss increases, and the average delay approaches the asymptotic value of approximately 0.7286ms-0.7287ms. However, in this paper a maximum of just 196 vehicles was considered; therefore the network is not saturated. The average delay should also increase if the vehicle density increases until the network is overloaded.

Some evaluations, which are only of the physical layer of the 802.11p, are also proposed in [23] [56] [40] [57]. In [23], the physical layer is evaluated by using a realistic non-stationary vehicular channel model. Several channel estimators are simulated and compared in this work. Three kinds of estimators are defined based on the pilot structure, that is, block-based, comb-based and block-comb-based estimators. The simulation



results indicate that the channel estimation performance is strongly influenced largely by two factors: the strength of the diffuse components, and the SNR. Whereas comb-based estimators perform best in environments with rich diffuse components and high SNR, the opposite is true for block-based channel estimators to perform well. Furthermore, in situations of a poor LoS contribution, an acceptable frame error rate is not achievable, even at high SNR values. Therefore, it is indicated that more complex channel estimation and equalisation techniques, based on the current standard pilot pattern, need to be developed in order to cope with the properties of the vehicular radio channel. In [56], the authors present a realistic, yet computationally inexpensive simulation model for IEEE 802.11p radio shadowing in urban environments. The proposed model is able to accurately estimate the signal attenuation caused by buildings and other obstacles. It can also estimate realistic path loss values for ongoing radio communication very efficiently. The authors of [40] evaluate the PER performance degradation of the 802.11p PHY due to the time-varying channel and the Doppler Effect. A MATLAB simulation model is developed and used to analyse the system performance in the context of high mobility. The simulation results show that the estimation process is affected the most by the rapid changes in the channel, severely affecting the PER performance (PER increases when the speed increases), while the Inter Carrier Interferences (ICI) have little or no impact on the performance at small data rates. It is indicated by the above mentioned authors that the use of two receiving antennas can significantly improve the PER. In [57], the maximum communication distance for IEEE 802.11p transceivers in a highway scenario is evaluated based on simulation. The simulation results indicate that the envisioned communication range of 1000m in the IEEE 802.11p Project Authorisation Request (PAR) cannot be reached with 2W EIRP and 3Mbps data rate in the investigated highway scenario. Of the successful communications, 90% were conducted at a distance of less than 750m.

In [48], 802.11p and Worldwide Interoperability for Microwave Access (WiMAX) technologies are compared in a highway scenario. Two scenarios, to study the impacts of the source data rate and vehicle speed on 802.11p/WiMAX, are proposed. Subsequently, the coverage, average throughput, and end-to-end delay are evaluated for different vehicle speeds, traffic data rates, and network deployments. Finally, based on the simulation results, it was concluded that WiMAX offers large radio coverage and high data rates and that 802.11p is better suited to low traffic loads, where it offers very short latencies, even at high vehicle speeds. However, the simulation scenario presented in this paper only considers one vehicle; hence, the access collisions among the vehicles are not considered.

The simulation-based evaluation is one of the most efficient and economical ways to analyse the performance of the 802.11p in VANETs. The simulation parameter settings should be very carefully considered in order to yield a realistic and accurate result. Some

parameters, such as the communication range, bit rate and transmission power are closely related to the application type. With regard to the safety applications of DSRC, as defined in [59] and [60], the delay required is  $100ms$ , and the expected communication range is from  $100 - 1000m$ . The WSM is sent on channel 172 using  $6 Mb/s$  data rate. The maximum transmitting power is defined as  $800mw$  in [10],  $760mw$  in [13].

### 2.3.3 Test-based Evaluation

In [30], the authors present an IEEE 802.11p full-stack prototype for the implementation of data exchange among and between vehicles and the roadway infrastructures. Three scenarios are considered in this work: hard-brake, accident, and tolling services. The performance of the proposed prototype is tested under realistic urban and suburban driving conditions. The results derived from the test indicate that communication is possible with a low FER or Bit Error Rate (BER) at approximately  $400m$  with  $22dBm$  EIRP. It is also indicated in this paper that communication is possible at higher distances, approximately  $1000m$  with the same EIRP of  $22dBm$ . In addition, the best position for the location of the antenna was also tested and the roof location was identified as the best place. However, the OFDM PHY layer was not implemented and a single BPSK modulation with  $1 Mbps$  of data rate was used in that system. The modulation affects the communication range. Therefore, the results obtained may not be very accurate.

The authors in [52] carried out an infrastructure-to-vehicle trial using an IEEE 802.11p prototype on an actual highway, the A12, in Tyrol, Austria. This paper presents the results of the evaluation of the average downstream performance of the PHY. It is indicated that shadowing effects, mainly caused by trucks, lead to a strongly fluctuating performance of the link quality, especially for settings with long packet lengths and high vehicle speeds. The maximum achievable range obtained in this paper is approximately  $700m$  with  $3Mbps$  data rate and  $15.5dBm$  EIRP, where the frame-success-ratio is continuously larger than  $0.25$ . The maximum data volume that can be transmitted when a vehicle is driven by a roadside unit is achieved at low data rates of  $6$  and  $9Mbit/s$ .

In [21], the reliability of 802.11p was analysed using real-world application data traffic, collected from three vehicles communicating with each other under conditions involving both an open field traffic environment and freeway traffic on a highway in the US. The reliability was analysed based on the metrics of the packet delivery ratio and the distribution of consecutive packet drops. The experimental data indicates that 802.11p provides an adequate degree of communication reliability under both traffic conditions, and that the packet drops do not occur in bursts, even in the harsh freeway traffic environment. However, while this scenario considers just three vehicles, the reliability of 802.11p in a high data traffic environment was not evaluated.

In [51], the authors evaluate and discuss the required SNR for the specific FER



threshold of 0.1 from IEEE 802.11p PHY performance measurements, carried out on an Austrian highway. The required SNR for achieving a FER less than 0.1 is estimated for various configurations of data rate, packet length, and vehicle speed. Two measurement scenarios are considered in this work: Low RSU and High RSU. Comparing the high RSU and the low RSU, the required SNR is always smaller in the case of the high RSU, with a mean difference of parameter settings of 4.6 dB overall. In addition, considering the LoS between the RSU and the OBU, it is strongly recommended that the position of the RSU antenna should be higher than the tallest of the vehicles.

Test-based evaluations can provide a realistic evaluation result in terms of communication range, SNR and signal block. However, due to the high cost of the test environment, some key metrics of QoS such as for instance, collision and throughput are not easily evaluated via a test-based evaluation method.

## 2.4 Enhancements of 802.11p

The previous section addressed the existing evaluations of the 802.11p standard, and the performance of 802.11p was discussed and analysed. In this section, the existing enhancements of the 802.11p standard are surveyed and discussed for the MAC and the PHY layers respectively.

### 2.4.1 Enhancements of MAC

Certain algorithms to improve the throughput of the 802.11p standard are proposed in [66] [55] and [41]. In [66], it was indicated that the MAC parameters for the original IEEE 802.11p MAC protocol may lead to undesired throughput performance because the Back-off window sizes are not adaptive to the dynamics in the numbers of vehicles attempting to communicate. Thereafter, in this paper, two algorithms are proposed to address this problem. The first is named the Centralised Enhancement Algorithm (CEA) in which the exact information about the number of such vehicles is used to calculate the optimal window size. However, the exact number of concurrent transmitting vehicles is difficult to obtain in the real network. Subsequently, the authors propose a Distributed Enhancement Algorithm (DEA) which estimates the number of concurrent transmitting vehicles and adapts the window size. The simulation results indicate that the proposed DEA could improve the throughput of the network from 7% to 79% for different networks. However, the estimation of the number of concurrent transmitting vehicles is not very accurate and hence the gain of throughput is not stable for different networks. In [55], the authors propose a Vehicular Channel Access Scheme (VCAS) to optimise the channel throughput. In the VCAS, all OBUs have to listen to CCH for receiving WAVE announcement frames, which carry WSA information and are broadcast

by RSU during CCH intervals. Thereafter, a number of OBUs with similar transmission rates are grouped into one SCH by using the transmission distance threshold carried by the WSA frame. The group sizes of channels are controlled in order to fulfil the fairness requirement. In order to flexibly compromise the trade-off between throughput and fairness, a marginal utility model is proposed. Simulation results demonstrate that the proposed VCAS with marginal utility provides a flexible method to handle versatile vehicular scenarios. However, VCAS requires that RSU uses two or more transceivers, which might not be suited to certain environments. A Detection-Based MAC protocol is presented in [41], in which RTS/CTS (Request To Send/Clear To Send) is used to detect network congestion through message exchange and to predict the number of competing nodes. Subsequently, the nodes dynamically adapt the contention window size based on the network status detection and the prediction of the competing nodes. The proposed Detection-Based MAC outperforms the IEEE 802.11 Base Access and RTS/CTS in total throughput by plus 50.4% and 62.6%, respectively; and the collision rate by 48.8% and 10.6% less, respectively. Besides, it is proved that Detection-Based MAC has the least standard deviation of delay. However, the paper under discussion does not clearly explain how the nodes guarantee the accuracy of the predicted number of competing nodes.

In [28] [65] [19], some enhanced algorithms are proposed for the service channels. Cooperative Reservation of SCH (CRaSCH) is suggested. The main concept of CRaSCH is to exploit, as much as possible, the WSA frames sent on the CCH interval to spread out information regarding the SCH occupancy among 1-hop and 2-hop neighbouring providers, in order to ensure the setup of channel-disjoint WBSSs. Two approaches: Proactive Gossiping and Reactive Gossiping are proposed in CRaSCH to reduce the cases where two or more providers choose the same service channel for non-safety traffic delivery. Simulation results show that CRaSCH outperforms 802.11p in both highway and urban scenarios with only a few additional bytes overhead. In [65], the authors propose an improved channel access scheme in order to allow a station to stay on a service channel for as long as it requires before returning to the control channel. The main concept behind this algorithm is to cut off CCH in order to extend SCH and hence to improve the service channel utilisation. However, in vehicular networks the safety messages, which are transmitted during CCH, enjoy a higher priority; hence the CCH interval must be guaranteed. In addition, only one user is considered in this paper and the effects on its neighbours, incurred by changing channel intervals, are not analysed. In [19] a WAVE-based Hybrid Coordination Function (W-HCF) protocol is proposed to leverage controlled access capabilities on top of the basic contention-based access of the IEEE 802.11p. The W-HCF scheme relies on alternate centralised and distributed channel access over SCHs, in order to satisfy the requirements of QoS-sensitive information applications, while still keeping bandwidth available for non QoS-sensitive services. The central notion of W-HCF is to reserve part of the SCHs intervals for QoS-

sensitive applications in which the access control is centralised. The remaining parts of intervals are for non QoS-sensitive applications in which the access control is distributed and contention-based. The W-HCF can offer a stable performance in meeting both the time delivery constraints and throughput requirements of non-safety infotainment applications, regardless of the traffic load. However some extra signalling is required by W-HCF for resource reservation and polling which consequently increase the traffic load. Furthermore, the end-to-end delay could be prolonged by W-HCF due to the centralised access control proceeding when the traffic load is low.

In order to reduce the collision rate in 802.11p, some collision avoidance algorithms are suggested in [31] [53] [22]. A solicitation-based IEEE 802.11p operation mode, known as WBSS User Initiation Mode (W-UIM), is proposed in [31] to avoid packet collisions by using a polling scheme. In W-UIM, a WBSS user solicits data frames destined for itself in an opportunistic manner, by requesting the transmissions of the frames from a WBSS provider by a WAVE-poll frame. Throughput analysis proposed in this paper reveals that W-UIM achieves a stable saturated WBSS throughput, which is higher than IEEE 802.11, irrespective of the number of contending and moving-away WBSS users. However, the analysis is only based on a theoretical calculation and is not verified by simulation or realistic experiment. Furthermore, the analysis method is not completely or clearly presented. In [53], the Coupon Collector's Problem [18] in the IEEE 802.11p MAC is presented. It is indicated that much time for collecting all vehicle information is needed owing to the randomness of the channel access in the IEEE 802.11p MAC and the unreliable nature of the safety beacon broadcast. Therefore, the authors proposed an approach to solve the Coupon Collector's Problem, which suppresses the WAVE nodes that succeeded, in the previous attempt, in contending for the channel for the next few safety beacon intervals. However in this algorithm, the application level feedback is used and transmitted in order to let the successful nodes know that they have succeeded, which consequently increases the network traffic. Furthermore, the safety beacon is time critical; hence the suppression of the safety beacon may not be suited to the vehicular networks. In [22], a strict priorities algorithm for 802.11p MAC protocol is advocated. The central notion of the proposed algorithm is to prolong the AIFS of the lower-priority frames in order to reduce the higher-priority frames contention and furthermore improve the performance of higher-priority frames. The proposed AIFS is determined as  $AIFS_{Lower} = AIFS_{Higher} + CW_{maxHigher}$ . The simulation results indicate that the proposed algorithm is effective in reducing delay, jitter and losses for the most critical messages, even in high-traffic conditions; however, this leads to an increase in the delay experienced by lower-priority frames.

In [63] a Variable CCH Interval (VCI) multichannel MAC Scheme is proposed. The VCI MAC scheme adopts a new coordination mechanism to provide contention-free SCHs by a channel reservation on CCH. However, the CCH interval reserved for safety

message delivery has not been properly calculated. Firstly, in the VCI MAC scheme, only the safety message transmission time is counted in the CCH interval calculation. The Back-off time should be counted and hence the time duration needed by the safety message delivery should be much longer than the result obtained in [63]. Secondly, the safety message frequency is considered as 2 per second which is too low to meet the safety application requirement. In addition, in the analytical model only the saturation scenario is considered, which does not suit the real-world network environment.

In [24], a Self-organizing Time Division Multiple Access (STDMA) for real-time data traffic between vehicles is proposed. In STDMA, the time is divided into frames as in a Time Division Multiple Access (TDMA) system, and all vehicles strive for a common frame start. These frames, which are one second long in this study, are further divided into slots, which typically correspond to the duration of one packet. Subsequently, each vehicle selects proper slots after four different phases: *initialisation*, *network entry*, *first frame*, and *continuous operation*. STDMA attempts to ensure that each vehicle is able to access the channel regardless of the number of competing nodes. It has been demonstrated via simulation that STDMA performs better than CSMA under the periodic vehicle-to-vehicle broadcasting scenario. Thereafter, CSMA and STDMA in [25] are compared for broadcasting periodic position messages in a realistic highway scenario. The scalability in terms of the number of vehicles that the VANET can support using metrics, such as channel access delay, probability of concurrent transmissions and interference distance, is investigated. It is concluded in [25] that the main difference between the MAC methods, CSMA and STDMA, occurs where concurrent transmissions take place in space. In CSMA, there are randomly distributed, whereas in STDMA there are scheduled, using the side information from the position messages. Therefore, when the network load in a VANET increases, STDMA becomes increasingly more attractive compared to CSMA. STDMA may also provide increased reliability due to reduced interference for nodes situated closest to the current transmitters. STDMA provides fairness, predictable channel access delay, and good scalability, since all channel requests turn into channel access, which are scheduled far apart in space. However, as indicated in [26], with respect to high vehicular mobility, this renders the MAC coordination very difficult; hence the performance of STDMA needs further evaluation, particularly with regards to the coordination issue.

In [17], the unfairness problem, due to the relative speed among vehicles, is identified. It is indicated that the vehicle with a higher speed has less opportunity to access a channel due to the shorter travel time in the communication range. Two priority channel access schemes based on vehicle mobility are then proposed to address the unfairness problem. In the said schemes, the vehicle with a higher speed or lower transmission probability has a higher priority to access the channel. The proposed schemes are proven to be able to provide better fairness and performance in certain scenarios. However, the

priority adaption could affect the performance of high priority data. The higher priority data are normally very critical to the delivery reliability and transmission delay. As a result, the affect on the performance of higher priority data should be carefully considered.

From the recent enhancements of 802.1pMAC, it may be observed that the network throughput and collision avoidance have recently come into focus. Many researchers show more interest in the SCH channel. As a result, the CCH channel needs more attention since the safety related messages, which are critical to the reliability and delay, are transmitted on CCH.

### 2.4.2 Enhancements of PHY

Compared to the MAC, the PHY has fewer enhancements. The algorithms proposed in [34] and [54] address the channel estimation and equalisation problem. In [34], the authors indicate that a narrow coherence bandwidth and short coherence time contribute to a degraded physical layer performance in V2V channels. The traditional, preamble based equalisation scheme adapted by 802.11p is insufficient for combating the V2V channel effects. Subsequently, four equalisation schemes: Comb Pilot Interpolation, Comb Co-Pilot Interpolation, Constellation-Aware Data Equalisation, and Spectral Temporal Averaging, are proposed using the existing pilot subcarriers or using the pilot subcarriers in combination with data subcarriers. The proposed schemes were tested on real V2V waveforms and indicated that adding greater reliance on data to aid in channel estimation improves the packet error rate. The experiment data also indicates that the spectral temporal averaging outperforms the other proposed schemes, and decreases the PER significantly. In addition, these equalisation methods are receiver-centric and will not require a change to the 802.11p standard. In [54], the performances of Vehicle-to-Anything (V2X) communications based on the IEEE 802.11p WAVE system are investigated in practical small-scale fading models re-designed for computer simulations. The problem of the conventional least squares (LS) channel estimator using two long training symbols adopted by 802.11p is addressed, and an enhanced linear minimum mean square error smoothing-aided decision directed (LSA-DD) channel estimator is proposed to track the time variation of fading channels and mitigate noise enhancement. However, the proposed LSA-DD is only compared with LS in the worst channel in which the PER is always 1 for LS; hence the evaluation offered is not comprehensive.

In [44], the performance of IEEE 802.11p PHY employing turbo coding is evaluated based on MATLAB simulation and Field Programmable Gate Array (FPGA) implementation. The BER vs. SNR for different kinds of modulation schemes in different channels is simulated. Compared to other techniques, the turbo coding scheme achieves a significant improvement in the performance of 802.11p, while the turbo coding gain can reach up to 6dB, and the resource overhead is always below 10%.

In [15], the performance of spatial diversity for broadcast safety applications in a V2V environment is presented. The performances of Multi-Input Multi-Output Space-Time Block Coding (MIMO-STBC) and Single Input Single output (SISO) systems are compared. It is demonstrated that MIMO-STBC offers a 43% to 80% range extension as compared to a SISO system. Consequently, however, more antennas are needed in MIMO-STBC.

## 2.5 Present Situations and Future Research directions of 802.11p

In the previous two sections, the evaluations and the enhancements of the 802.11p standard are presented and discussed. In this section, the present situations of the 802.11p standard, based on the previous discussions, are summarised. Subsequently, the future research directions of the 802.11p are identified.

### 2.5.1 Present Situations of 802.11p

The present situations of the 802.11p standard are concluded and presented in some important metrics, as indicated below:

1. Throughput: Four analytical models are proposed to analyse the throughput of 802.11p in [37] [38] [35] [46] respectively. All these models are based on Markov Chains. In order to improve the performance of 802.11p in terms of throughput, some enhanced MAC protocols, such as CEA and DEA in [66], the VCAS in [55] and the Detection-Based MAC in [41], are advocated. VCAS requires that RSU possesses two or more transceivers. The DEA and Detection-Based MAC use a similar concept: that the contention window size be adapted according to the network status. The main difference between the DEA and the Detection-Based MAC lies in how to detect the network status. However, the status of the network obtained by these two algorithms has, so far, not been very accurate.
2. Scheduling: The effect of changing the CCH/SCH duty cycle is analysed in [46] [47] [65] [63]. In [46] and [47], the numbers of users on CCH and SCH are discussed when the CCH interval is from 9ms to 45ms. In [65], an algorithm is proposed to improve the SCH channel access scheme by cutting off CCH in order to extend SCH. The VCI MAC scheme in [63] adopts a new coordination mechanism to provide contention-free SCHs by a channel reservation on CCH. Thus, all the proposed algorithms only improve the service channel utilisation without considering the control channel utilisation. The CRaSCH proposed in [28] can reduce the case where two or more nearby providers select the same service channel by



adopting Proactive and Reactive Gossiping approaches. The W-HCF proposed in [19] offers a stable performance of non-safety infotainment applications regardless of the traffic load. However, some extra signalling is required by W-HCF for resource reservation and polling, which consequently increases the traffic load. In [29] and [17], the idea of adapting the EDCA parameter sets in order to improve the performance of 802.11p under some particular circumstances, was proposed. The effects of the different EDCA parameter sets on network performance are analysed and discussed.

3. Collisions: The collision avoidance function is very important to the 802.11p standard since it may significantly affect the QoS of VANETs. In [27], it was demonstrated that the collision probability increases if traffic flow increases. Thereafter, four algorithms were proposed, in order to reduce the collisions in VANETs. The Detection-Based MAC proposed in [41] can reduce the collision rate by adapting the contention window size based on the network status detection and the prediction of the competing nodes. In [53], a collision avoidance algorithm is proposed to address the Coupon Collector's problem by suppressing some contending nodes. The W-UIM proposed in [31] uses a polling scheme to avoid packet collisions. The strict priorities algorithm proposed in [22], can reduce the higher-priority frames collision by suppressing the lower-priority frames contention.
4. Latency: Due to the high mobility of vehicles, latency is a critical parameter for the designing of MAC protocol in VANETs. In [48] it is indicated that, compared with WIMAX, the 802.11p is better suited to low traffic loads, where it offers very brief latencies, even at high vehicle speed. However, the latency is significantly affected by traffic. While in [36], it was concluded that only when the total amount of traffic offered approaches 1000 packets per second, does the delay on the control channel become longer than 100ms, which is too high for safety critical applications, in [33], it was indicated that the delay on the control channel is 1s with a total of offered traffic of 3000 packets per second.
5. Communication range: Four studies have evaluated the communication range of 802.11p in [30] [52] [57] [36] respectively. The results obtained are shown in Table 2.3. It may be observed that the communication range depends greatly on the set of EIRP, FER and data rate. It can also be noted that 802.11p standard is adequate in terms of communication range (around 1000m expected in WAVE) with a proper set of EIRP and data rate. In [15], an enhanced algorithm MIMO-STBC, rather than a SISO system, was proposed, offering an extension within the 43% to 80% range by employing more antennas.
6. Channel estimation and equalisation: Several channel estimation models were pro-

posed in [23] [56] [40]. In [23], some of the channel estimators are simulated and compared. Furthermore, in situations of poor LoS, they indicated that 802.11p PHY does not perform well, even at high SNR values, and hence more complex channel estimation and equalisation techniques need to be developed. The model proposed in [56] is able to accurately estimate the signal attenuation caused by buildings and other obstacles. The model proposed in [40] is designed for evaluating the PER performance degradation of the 802.11p PHY caused by the time-varying channel and the Doppler Effect. Some enhanced algorithms are proposed to address the channel estimation and equalisation problem discussed in [34] and [54]. In [34], four equalisation schemes are proposed and the spectral temporal averaging scheme is demonstrated to be the best to decrease PER significantly. In [54], the LSA-DD channel estimator was proposed to track the time variation of fading channels and to mitigate noise enhancement.

7. Mobility: The effects of high speed mobility in VANETs are evaluated in [49] [40] [17]. In [49], it is proven that packet loss is not affected by the vehicle speed. However, in [40], the opposite result is obtained that PER increases when vehicle speed increases. In [17], the mobility effect is analysed in terms of channel access opportunity.

### 2.5.2 Future Research Directions of 802.11p

VANETs possess specific characteristics due to the high speed mobility of the vehicle, for example, rapid changes of topology, potentially large-scale, veritable network density and so forth [67]. These characteristics indicate important implications for the design of protocol in VANETs. Based on the characteristics of VANETs and the present situation of the 802.11p standard, the suggested future research directions of the 802.11p standard are furnished as follows:

1. Throughput improvement: In VANETs, many safety messages need to be broad-

Table 2.3 Communication range

SN	Communication Range(m)	FER	EIRP (dBm)	Data Rate (Mbps)	Evaluation	Reference
1	400	$\leq 0.11$	22	1	experiment	[30]
2	1000	not evaluated	22	1	experiment	[30]
3	700	$\leq 0.75$	15.5	3	experiment	[52]
4	750	$\leq 0.1$	33	3	simulation	[57]
5	2500	not evaluated	44.8	3	simulation	[36]



cast among vehicles periodically, while communication between vehicle and RSU is also needed in order to realize intelligent transport control. Hence, high throughput is required in VANETs. Due to the characteristics of VANETs, the network density and the topology of VANETs are not stable, therefore an intelligent MAC protocol is needed that is able to dynamically adapt its parameters, based on the network status, in order to improve the network throughput. In [66] and [41], certain algorithms are proposed and further research is needed to improve these network detection algorithms.

2. Scheduling optimisation: The principle of adapting the intervals of CCH and SCH is suggested in [46] [47] [65] [63]. The algorithm proposed in [65] could improve the channel utilisation when there are a greater number of services messages and fewer control messages. Due to the variable network density in VANETs, a scheduling optimisation algorithm is needed to adapt the intervals of CCH and SCH, depending on the network status. In addition, the network detection algorithms could also be adapted to detect the said status.
3. Traffic control: It is stated in [27] that the number of contention cases increases if the traffic flow increases. Contention incurs collisions; in other words, the number of collisions increases if the traffic flow increases. Hence, traffic control is the key to solving the collision problem in VANETs. Latency is very critical in VANETs, due to the brief but urgent time needed by a critical safety application. It is evident, when comparing the results of [36] and [33], that high traffic leads to longer periods of latency. Hence, traffic control is also the key to reducing latency in VANETs. Consequently, traffic control technology is needed to reduce collisions as well as latency in VANETs.
4. Channel estimation and equalisation: The poor LoS problem caused by buildings, trees or big trucks, as indicated in [23] and [56], requires more complex channel estimation and equalisation techniques which consider the characteristics of VANETs. In addition, as indicated in [34] and [54], enhanced channel estimation and equalisation techniques can improve the throughput of the network by decreasing the PER and noise.
5. Mobility effect: High speed mobility is a basic characteristic of VANETs, and hence the effect of high speed mobility needs to be considered in the VANETs protocol design. However the existing evaluations proposed in [49] and [40] yield a conflictive result. Hence, further research needs to be carried out in terms of the mobility affection.

## 2.6 Conclusion

As discussed, VANETs exhibit certain characteristics due to the high speed mobility of the vehicle; for example, rapid changes of topology, potentially large-scale, veritable network density and so forth [67]. These characteristics indicate important implications for the design of protocol in VANETs. Based on the characteristics of VANETs and the above discussions, two future research directions of the 802.11p standard are identified as follows: 1. Scheduling optimisation: The idea of adapting the intervals of CCH and SCH is proposed in [46] and [65]. The algorithm proposed in [65] can improve the channel utilisation when there are a greater number of services messages and fewer control messages. Due to the variable network density in VANETs, a scheduling optimisation algorithm is needed to adapt the intervals of CCH and SCH, depending on the network status. 2. QoS enhancement: In [27], it is stated that the number of contention cases increases if the traffic flow increases. Contention incurs collisions; in other words, the number of collisions increases if the traffic flow increases. Hence, traffic control is the key to solving the collision problem in VANETs. Latency is very critical in VANETs, due to the short time needed by a critical safety application. It is evident, when comparing the results of [36] and [33], that high traffic leads to longer periods of latency. Hence, traffic control is also the key to reducing latency in VANETs. To put it another way, the QoS of VANETs is greatly affected by the traffic. The most efficient way to reduce the traffic is to extend the channel interval or offer more channels because the total network traffic cannot be reduced in order to meet the application requirement in VANETs. In addition to this, the QoS of VANETs equipped with multi-transceiver needs to be analysed; furthermore, a QoS enhancement multi-channel MAC protocol needs to be developed in order to schedule and optimise the multi-channel access.



# Chapter 3

## Simulation Platform

### 3.1 Introduction

In this chapter, the simulation platform used to evaluate the performance of IEEE 802.11p and validate the proposed algorithms is discussed. Chapter 3 is organised as follows: In Section 3.2, some commonly used simulators are compared and one of them is chosen as the simulation platform in this study. The simulation model including the related simulation frameworks and dedicated simulation models are presented in Section 3.3. Finally, a conclusion is offered in Section 3.4.

### 3.2 Comparison of Simulators

There are currently many different simulators. Some of the frequently used ones are described below:

**ns-2** ns-2 [ns2] is the second version of ns (Network Simulator). It is a well-established, discrete event simulator that provides extensive support for simulating TCP/IP, routing and multicast protocols over wired and wireless networks. The ns-2 includes the most common network technologies and applications and is freely available for research and education. It is designed for Unix-Systems yet also runs using Windows CygWin [cyg].

**OPNET** OPNET [opn] is a commercial platform for simulating communication networks. Conceptually, the OPNET model comprises processes based on finite state machines; these processes communicate as specified in the top-level model. The wireless model is based on a pipelined architecture to determine connectivity and propagation among nodes. Users can specify frequency, bandwidth, and power among other characteristics, including antenna gain patterns and terrain models.

**NCTUns** NCTUns [64] is a commercial tool that closely integrates communication/network simulation with road/traffic simulation. NCTUns is a C++ based simulator running on the Linux Fedora platform. Besides its support for various communication models and network protocols, it has supported the implementation of road networks and many realistic microscopic vehicle mobility models that have been implemented. NCTUns can provide a fast feedback loop between network simulation and traffic simulation. This capability enables a user to use NCTUns to study novel ITS applications in which a vehicle needs to change its moving behaviour immediately after receiving a message from a neighbouring vehicle or from the infrastructure network.

**OMNeT++** Objective Modular Network Test-bed in C++ (OMNeT++) [62] is a public-source, component-based, modular simulation framework. Its primary application area is that of communication networks. OMNeT++ exhibits a generic and flexible architecture which also makes it successful in other areas such as IT systems, queuing networks, hardware architectures, or even business processes.

OPNET and NCTUns are commercial simulators, which means that their manufacturers will not provide the source code of the software or the affiliated packages to general users without payment. For academic use, the manufacturers may provide a free license for use, with some limitations; reapplications for the free license are required after a certain period; possibly bringing some risks and inconveniences to the use of these commercial simulators. ns-2, and OMNeT++ are open source simulator and were considered for this study. OMNeT++ was finally selected as the simulator of choice. The reasons for this were:

**Flexibility** OMNeT++ is a flexible and generic simulation framework. It can simulate anything that can be mapped to active components that communicate by passing messages, whereas ns-2 was designed as a (TCP/IP) network simulator, and it is difficult to use this method to simulate things other than packet-switching networks and protocols. It employs highly detailed and hardcoded concepts regarding nodes, agents, protocols, links, packet representation, and network addresses and the like, which renders it difficult to manage when attempting even slight variations.

**Model Management** The OMNeT++ simulation kernel is a class library, and the models in OMNeT++ are independent of the simulation kernel. Researchers can write their components (simple modules) against the OMNeT++ simulation kernel API. OMNeT++ sources are never patched by models. Simple modules are therefore reusable, and can be freely combined like LEGO blocks to create simulations. By contrast, in ns-2, the boundary between the simulation core and the models is blurred, without a clear API.

**Documentation** OMNeT++ has a well written and up-to-date manual and the simulation API of OMNeT++ is more mature and much more powerful than that of ns-2. The ns-2 documentation is fragmented and there is no clear dividing line between the models and the ns-2 simulation library.

**Running Environment** While OMNeT++ runs on Windows, Linux, Mac OS X, and other Unix-like systems. the ns-2 can just run on Linux and Mac OS X and Cygwin is needed if it runs on Windows.

**Simulation Model** This study focuses on the IEEE 802.11p and WAVE 1609.X. The 802.11p model is supported by both OMNeT++ and ns-2. However, to the best of my knowledge, the WAVE 1609.X model is only supported by OMNeT++ with the Vehicles in Network Simulation (Veins) model [32].

## 3.3 Simulation Model

In this study, the INET-2.0.0 [Ine] and Veins 2.0-rc2 [32] frameworks are used to build a dedicated 802.11p simulation model working on OMNeT++. In this section, the INET and Veins framework are introduced first; then the dedicated simulation models, which will be used in the 802.11p evaluation and enhancement verification in this study, are presented and discussed.

### 3.3.1 INET Framework

The INET Framework is an open-source communication networks simulation package for the OMNeT++ simulation environment. The INET Framework builds upon OMNeT++, and uses the same concept: modules that communicate by message passing. Hosts, routers, switches and other network devices are represented by OMNeT++ compound modules. These compound modules are assembled from simple modules that represent protocols, applications, and other functional units. A network is again an OMNeT++ compound module that contains host, router and other modules. The external interfaces of modules are described in NED files which explain the parameters and gates (i.e. ports or connectors) of modules, and also the submodules and connections of compound modules.

The protocols supported by INET-2.0.0 are listed in Table 3.1. has been supported as one of the 802.11 models. The key QoS metrics referred to previously, such as delay, collision and throughput, may be obtained from the simulation results. Therefore, in the beginning of this study, INET is used to evaluate the performance of 802.11p in safety applications. However, the CCH/SCH switching function has not been supported in INET.

Table 3.1 Protocol matrix.

Class	Protocol
Application	CBR/VBR HTTP File Transfer DHCP Video Voice Peer-to-peer
Transport	TCP UDP SCTP
Network	IPv4 ICMPv4 ARP IGMPv2 IPv6 ICMPv6 MIPv6 HIP
Routing	link-state routing OSPF BGP RIP RSTP
MANET Routing	AODV DYMO DSR OLSR
MPLS	MPLS LDP RSVP-TE
Wired	PPP Ethernet
Wireless	802.11a 802.11b 802.11g 802.11p 802.11s 802.1e 802.16 (WiMAX)

Fig. 3.1 Veins architecture

### 3.3.2 Veins Framework

Veins is an open source framework for running vehicular network simulations. It is based on two well-established simulators: OMNeT++, an event-based network simulator, and SUMO [sum], a road traffic simulator. The architecture of Veins is illustrated in Fig. 3.1. It extends the two abovementioned simulators to offer a comprehensive suite of models for IVC simulation. Road traffic simulation is performed by SUMO, which is well-established in the domain of traffic engineering. Network simulation is performed by OMNeT++ along with the physical layer modelling toolkit MiXiM [45], which makes it possible to employ accurate models for radio interference, as well as shadowing by static and moving obstacles. Both simulators are bi-directionally coupled and simulations are performed online. In this way, the influence of vehicular networks on road traffic can be modelled and complex interactions between both domains examined. To perform IVC evaluations, both OMNeT++ and SUMO are running in parallel, connected via a TCP socket. The protocol for this communication has been standardised as the Traffic Control Interface (TraCI). This allows bidirectional-coupled simulation of road traffic and network traffic. Movement of vehicles in the road traffic simulator SUMO is reflected in movement of nodes in an OMNeT++ simulation. Nodes can then interact with the running road traffic simulation, for example, to simulate the influence of IVC on road traffic.

The IEEE 802.11p and IEEE 1609.4 protocols are fully supported by the Veins Version 2.0, which was released in 2011. Therefore, since 2011, Veins has been selected as the simulator for this study. Its features are listed as follows:

- Based on 100% open source software offering unrestricted extensibility.
- Allows for online re-configuration and re-routing of vehicles in reaction to net-

work packets.

- Relies on trusted vehicular mobility model and implementation done by the Transportation and Traffic Science community.
- Relies on fully-detailed models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network layers, including multi-channel operation, QoS channel access, noise and interference effects.
- Can simulate city block level simulations in real time on a single workstation.
- Can be deployed on compute clusters for simulation in MRIP distributed parallel fashion.
- Can import whole scenarios from OpenStreetMap, including buildings, speed limits, lane counts, traffic lights, access and turn restrictions.
- Can employ validated, computationally inexpensive models of shadowing effects caused by buildings as well as by vehicles.
- Supplies data sources for a wide range of metrics, including travel time and emissions.
- Supported by solid and diverse user base from five continents.

### 3.3.3 Dedicated INET Simulation Models

The architecture of the dedicated simulation node based on INET model is depicted in Fig.3.2. The simulation node contains four layers: application layer, network layer, MAC layer and PHY layer. The corresponding INET models are also listed in Fig.3.2.

#### 3.3.3.1 Application Layer

In the application layer, the 'UDPBasicBurst' model is used since the WSM application is not supported by INET so far. In this model, UDP beacon messages can be generated according to the predefined interval. In 'UDPBasicBurst' model, the first burst starts at 'startTime' by immediately sending a packet; subsequent packets are sent at 'sendInterval' intervals. The 'sendInterval' parameter can be a random value, e.g.  $\text{exponential}(10\text{ms})$ . A constant interval with jitter can be specified as  $1s + \text{uniform}(-0.01s, 0.01s)$  or  $\text{uniform}(0.99s, 1.01s)$ . The length of the burst is controlled by the 'burstDuration' parameter. The time between burst is the 'sleepDuration' parameter. Some key parameters of this model are listed in Table 3.2.



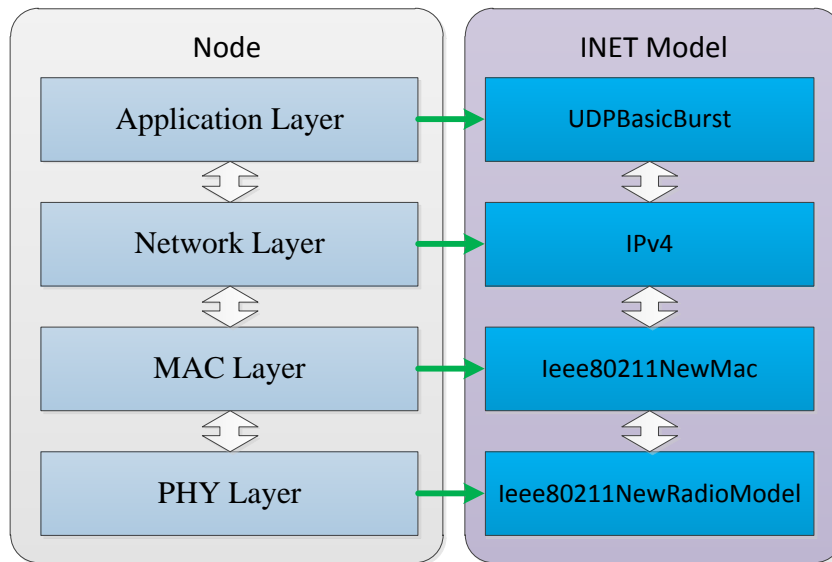


Fig. 3.2 Architecture of node\_INET

### 3.3.3.2 Network Layer

In the network layer, the IPv4 model is used to cooperate with the UDP application model. The IPv4 is able to serve several higher-layer protocols, such as TCP, UDP, ICMP, IGMP and RSVP.

### 3.3.3.3 MAC Layer

IN the MAC layer, the simulation node is built based on the 'Ieee80211NewMac' model. This model was developed from the 'Ieee80211Mac' model to support the 802.11p protocol. While the 'Ieee80211NewMac' model can support IEEE 802.11a/b/g/p, however, the CCH/SCH switching is not yet supported. Some key parameters of this model are listed in Table 3.3.

Table 3.2 Application layer configuration\_INET.

Parameter	Description
destAddresses	Space-separated list of destination IP addresses, "Broadcast" string as address for sending broadcast messages
startTime	Start of the first burst
stopTime	Application stop time
messageLength	Length of messages to generate, in bytes
burstDuration	Burst duration time
sleepDuration	Time between bursts
sendInterval	Time between messages during bursts
setBroadcast	Configure the socket for receive broadcast packets

Table 3.3 MAC layer configuration\_INET.

Parameter	Description
defaultAC	Ddefault AC category
AIFSN0	AIFSN for background
AIFSN1	AIFSN for best effort
AIFSN2	AIFSN for video
AIFSN3	AIFSN for voice
EDCA	Whether active the EDCA function
bitrate	Bitrate ("bps")
opMode	Operation model (802.11a/b/g/p)

### 3.3.3.4 PHY Layer

In the PHY layer, the simulation node is built based on the 'Ieee80211NewRadioModel'. The 'Ieee80211NewRadioModel' is an extended mode of the 'Ieee80211RadioModel'. The 802.11p protocol is supported. However, the CCH/SCH channel switching is also not supported. The key parameters of PHY layer are listed in Table 3.4.

## 3.3.4 Dedicated Veins Simulation Models

The architecture of the dedicated simulation node based on the Veins model is depicted in Fig.3.3. The simulation node contains three layers: application layer, MAC layer and PHY layer. The corresponding Veins models are also listed in Fig.3.3.

### 3.3.4.1 Application Layer

In the application layer, the simulation node is built based on the 'TestWaveApplLayer' model. The 'TestWaveApplLayer' model can generate WSM messages (beacons or

Table 3.4 PHY layer configuration\_INET.

Parameter	Description
snirThreshold	Signal-noise ratio
phyOpMode	Operation model (802.11a/b/g/p)
WiFiPreambleMode	WiFi preamble mode
aSlotTime	Duration of a slot (us)
aSIFSTime	Duration of a SIFS (us)
PHY_HEADER_LENGTH	Length of PHY header
Transmission power	Maximum transmission power

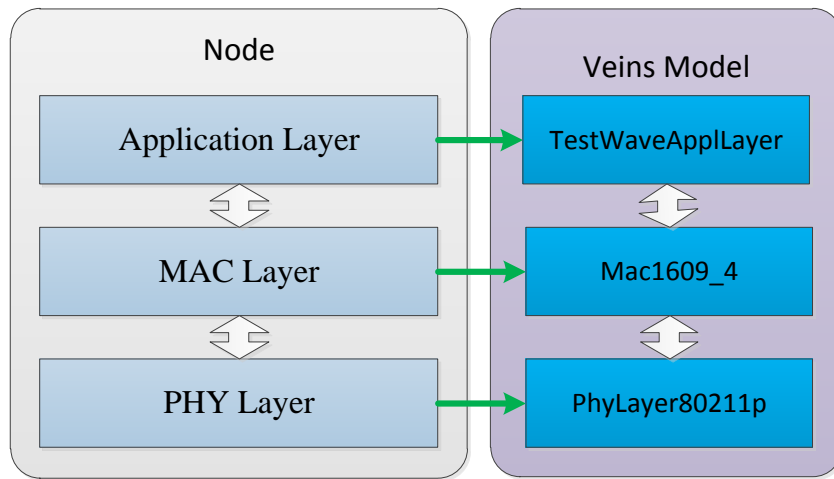


Fig. 3.3 Architecture of node\_Veins

data) according to a user's configuration. For example, the message coming interval, message size, transmission channel, access category and so forth, may be easily set and configured. Some key configuration parameters are listed in Table 3.5.

### 3.3.4.2 MAC Layer

In the MAC layer, the simulation node is built based on the Mac1609\_4 model. In this model, the key features of WAVE protocols are supported as follows.

- The CCH/SCH switching is fully supported.
- The EDCA process is fully supported, all the related parameters are set according to the DSRC/WAVE 1609.4 [14] and IEEE 802.11p [12] standard.
- The 7 kinds of channels as depicted in Fig. 1.1 are all supported.

Table 3.5 Application layer configuration\_Veins.

Parameter	Description
headerLength	Header length of the application
sendBeacons	Beacons sending frequency
beaconLengthBits	Length of a beacon packet
beaconPriority	AC of the beacon messages
beaconInterval	Interval between 2 beacon messages
maxOffset	Maximum sending down delay
sendData	Whether to send data
dataLengthBits	Length of a data packet
dataOnSch	CCH/SCH selection
dataPriority	AC of the data packets

- The four ACs are well supported, the simulation results for different ACs are well recorded.

### 3.3.4.3 PHY Layer

In the PHY layer, the simulation node is built based on the 'PhyLayer80211p' model. In the 'PhyLayer80211p' model, the CCH/SCH channel switching is supported and the key parameters of the PHY layer are listed in Table 3.6.

Table 3.6 PHY layer configuration\_Veins.

Parameter	Description
Sensitivity	Sensitivity of the physical layer [dBm]
maxTXPower	Maximum transmission power
Noise Model	Noise Model used (ThermalNoise)
AnalogueModel	Path loss model (SimplePathlossModel)
carrierFrequency	Carrier Frequency (5.890e+9)
headerLength	Length of the PHY header

## 3.4 Conclusion

In this chapter, the current simulation platforms are presented and compared in terms of flexibility, model management, documentation, running environment and simulation model. As mentioned, the OMNeT++ was finally selected as the simulator to evaluate the proposed algorithms in this study.

The dedicated simulation models used in this study are built on INET and Veins models. The details of the simulation models were then presented and discussed and some key parameters of the simulation models are described. The next chapter addresses the evaluation results based on the simulation models.



# Chapter 4

## Evaluation and Enhancement of 802.11p CCH

### 4.1 Introduction

This chapter concentrates on the 802.11p CCH. According to the IEEE 1609.4 coordination scheme [14], the channel time is divided into synchronisation intervals with a fixed length of  $100ms$ , consisting of  $50ms$  (including  $4ms$  guard interval) alternating CCH and SCH intervals. All vehicles stay in the control channel during the CCH period and switch to one of the six service channels during the SCH interval. The safety application messages are transmitted during CCH. However, as stated in [43], this is a significant concern if BSMs are constrained to be sent on the CCH during the  $50ms$  CCH interval, since there could be hundreds of devices in a given area and the collision rate could be very high. A special safety Channel 172 for safety communication is also proposed in [MO] and [43]. On the other hand, the  $50ms$  CCH interval could be too long and therefore wasted in a low vehicle density environment. Certain concepts for adapting the intervals of CCH and SCH are advocated in [46] [65] and [63]. In those studies, the CCH interval is reduced in order to improve the SCH service, but the authors do not consider extending the CCH interval for a high vehicle density environment in order to reduce the collision probability.

In this chapter, first of all a simulation based evaluation for the 802.11pMAC protocol is proposed in terms of the safety applications in VANETs. The simulation was based on the INET framework and two questions were addressed: (i) how does the IEEE 802.11pMAC protocol perform in safety applications with various CCH intervals? (ii) how many vehicles can be accommodated in VANET safety applications with various CCH intervals? After the evaluation, a CCH adaptive algorithm for the 802.11p MAC protocol was then proposed. The CCH interval was adapted according to the vehicle density environment in the proposed algorithm. In order to obtain an accurate CCH

adaptation threshold, the IEEE 802.11p MAC was then re-evaluated based on Veins [32] in terms of reliability and delay.

The remainder of this chapter is organised as follows. In Section 4.2, based on the INET framework, the IEEE 802.11p MAC was evaluated in terms of the safety applications. The IEEE 802.11p MAC was then re-evaluated based on the Veins framework to achieve the CCH interval adjustment threshold in Section 4.3. The proposed CCH adaptive algorithm for the 802.11p MAC is presented and evaluated in Section 4.4. Finally, the conclusions are provided in Section 4.5.

## 4.2 Performance Evaluation on INET

The performance of the IEEE 802.11p MAC protocol in VANET's safety applications is evaluated in the OMNeT++ network simulator [62] with the model of INET-2.0.0 [Ine]. The evaluation configurations and results are given in this section.

### 4.2.1 Evaluation Configurations

The simulation scenario is built on a highway segment of length  $1000m$ . The vehicles' speeds range from  $60$  to  $120km/h$ . The communication range is set as  $1000m$  since the expected radio range for a highway is up to  $1000m$  [50]. Each vehicle sends only one safety message every  $100ms$  in AC0. The safety message is generated randomly during  $[0, T_{CCH}]ms$  for each vehicle, where  $T_{CCH}$  denotes the CCH interval. The  $T_{CCH}$  is set as  $[10, 20, 30, 40, 50, 60, 70, 80, 90, 100]$  respectively in order to evaluate the performance of 802.11p MAC with various CCH interval. In this model, the safety messages can also be sent during SCH interval if there are still some of these safety messages remaining in the queue. Since the vehicle density  $D_{vehicle}$  could vary widely in a real network for different roads and time periods, the  $D_{vehicle}$  is set from  $0.01$  to  $0.5vehicles/m$ . As defined in [11], the message size for the BSM part I is 39 bytes and for Part II, the Vehicle Safety Extension frame of the BSM is less than 100 bytes. Hence, the packet size of safety related message should be less than 140 bytes. In this simulation, the packet size of any safety message  $L_{Safety}$  is set as the maximum value of 140 bytes. The other parameter settings used in this evaluation are listed in Table 4.1.

### 4.2.2 Evaluation Results

The IEEE 802.11p MAC protocol is evaluated in terms of collision, reliability, MAC delay and throughput respectively. The evaluation results are presented and discussed in this section.

Fig. 4.1 depicts the average collision probability  $P_{Coll}$  obtained from simulations,

Table 4.1 Parameter settings for evaluation.

Parameter	Value
Packet size $L_{Safety}$	140 bytes
MAC header $L_{MACheader}$	70 bytes
Message sending interval	10/s
Simulation time	10 s
Modulation and Data rate R	QPSK 6 Mbps
Communication range	1000 m
Transmission power $P_t$	800 mw
Transmitter&Receiver antennas heights	1.5 m
Transmitter&Receiver antennas Gain	0
aSlotTime	13 us
aSIFSTime	32 us
Signal to Noise plus Interference Ratio (SNIR) threshold	4 dB
Mobility model	BaseMobility
Propagation model	FreeSpace

where  $P_{Coll}$  is determined as  $P_{Coll} = \frac{N_{collision}}{N_{collision} + N_{received}}$  for each vehicle. Where  $N_{collision}$  denotes the number of collisions,  $N_{received}$  denotes the number of received messages. It may be observed that the collision probability increases significantly according to the increase in vehicle density and the decrease in CCH intervals. In this simulation scenario, each vehicle sends one safety message every 100ms. The increase in vehicle density means more vehicles will contend and attempt to send a message on each CCH interval. As a result, more collision will be caused. On the other hand, the decreasing of CCH interval will furthermore increase the contention due to the shorter CCH interval. It can also be concluded that the extending of CCH intervals could significantly reduce the collision probability when the vehicle density is lower than a threshold  $D_{Threshold}$  which is 0.2vehicles/m obtained in this simulation scenario.

Fig.4.2 shows the average MAC delay  $T_{MAC}$  for different vehicle density and CCH interval settings, where  $T_{MAC}$  means the delay occurred in the MAC layer. The  $T_{MAC}$  is the time elapsed since the safety message arrived at the MAC layer until the time that the message is sent out. The end-to-end delay  $T_{E2E}$  depends mostly on the MAC delay and can be derived from  $T_{MAC}$  as  $T_{E2E} = \frac{L_{Safety} + L_{MACheader}}{R} + T_{MAC} + \delta$ , where  $\delta$  is the propagation delay. In this study we have focussed solely on  $T_{MAC}$ . It can be observed from Fig.4.2 that the  $T_{MAC}$  increases according to the increase in vehicle density and a decrease of the CCH interval. The MAC delay is mostly caused by the Back-off time. The increase of vehicle density as well as the decrease of the CCH interval will cause more contention and more Back-off. As a result, a longer MAC delay is caused. In



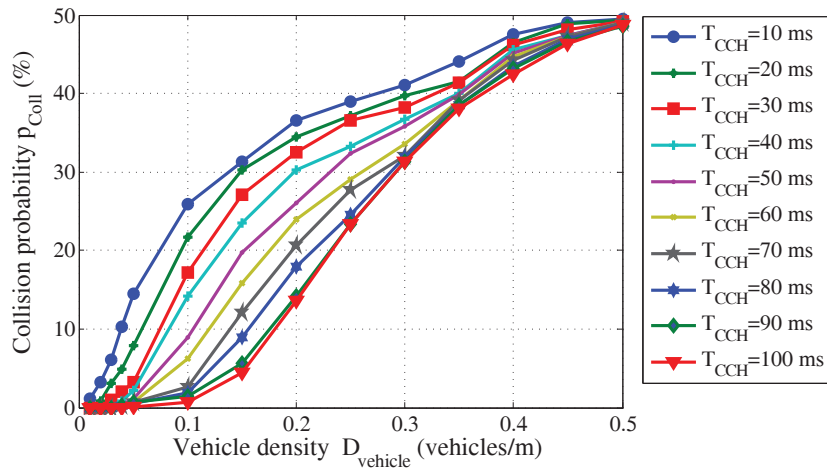


Fig. 4.1 Collision probability

addition, the MAC delay is always less than  $100ms$  in all these simulation scenarios. This indicates that IEEE 802.11p MAC protocol can satisfy the latency requirement (less than  $100ms$ ) in VANET safety applications.

Fig. 4.3 illustrates the average safety messages' delivery reliability,  $P_{Reliability}$ , for different vehicle density and CCH interval setting. It can be observed that the reliability decreases according to an increase in vehicle density and a decrease in CCH interval. The reliability is closely related to the collision probability. As discussed earlier, the increase of vehicle density as well as the decrease of the CCH interval will cause more collisions and consequently reliability will become worse. It can also be seen that the reliability is lower than 90% when the vehicle density is greater than  $0.15vehicles/m$ . Hence, the reliability for the domain  $0 \leq D_{Vehicle} \leq 0.15$  is selected and depicted in Fig. 4.4. The number of vehicles which may be accommodated in a network can then be derived from Fig. 4.4. The result obtained is indicated in Table 4.2. In addition, as illustrated in Fig. 4.2, the corresponding MAC delay for all the vehicles listed in Table.

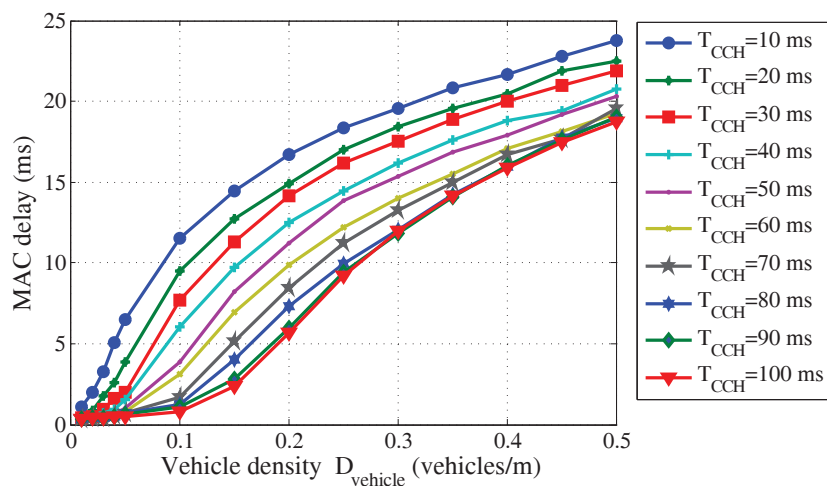


Fig. 4.2 MAC delay

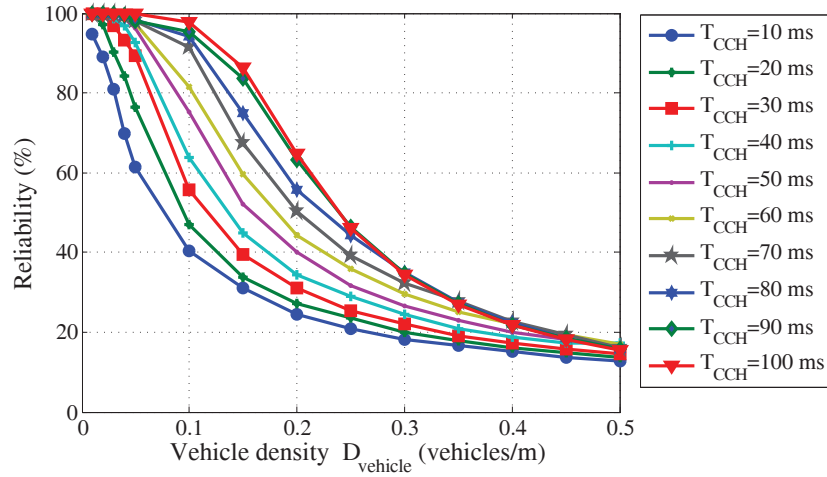


Fig. 4.3 Safety messages' delivery reliability

4.2 is less than  $4ms$ . As discussed in Section 4.1, there is a  $4ms$  guard interval between CCH and SCH. Hence, for the accommodated number of vehicles, the safety messages can be sent out before the SCH interval.

The network throughput and successful throughput are shown in Fig. 4.5 and Fig. 4.6 respectively. Since the channel time in VANETs is divided into synchronisation intervals with a fixed length of  $100ms$ , the throughput for one synchronisation interval, rather than  $1s$ , is considered in this work. It can be observed that the bigger the  $T_{CCH}$

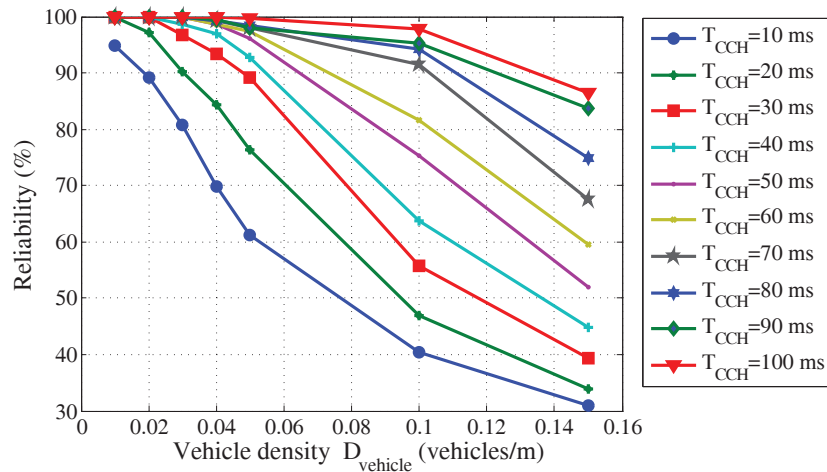


Fig. 4.4 Safety messages' delivery reliability-selected domain

Table 4.2 Accommodated number of vehicles on INET

$T_{CCH}(ms)$	10	20	30	40	50	60	70	80	90	100
Vehicles ( $P_{Reliability} \geq 99\%$ )	0	10	20	20	30	30	40	40	40	50
Vehicles ( $P_{Reliability} \geq 95\%$ )	10	25	35	45	55	60	70	80	90	125
Vehicles ( $P_{Reliability} \geq 90\%$ )	18	30	47	55	65	73	105	120	130	140

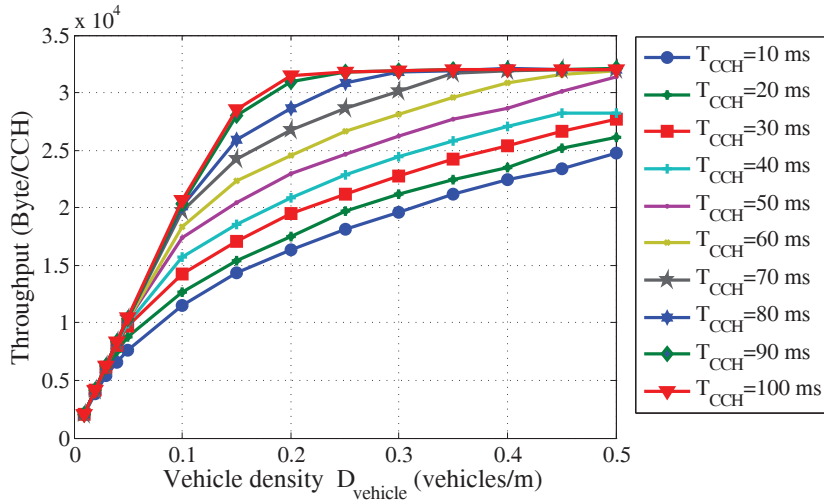


Fig. 4.5 Throughput

and  $D_{Vehicle}$ , the greater the throughput until the channel is becoming saturated. The successful throughput can be improved significantly by extending the CCH interval before the network becomes saturated ( $D_{Vehicle} = 0.2 vehicles/m$ ). The point where saturation occurs is just the threshold  $D_{Threshold}$  mentioned in the former collision analysis.

In conclusion, in VANET safety applications, the performance of the IEEE 802.11p MAC protocol can be significantly improved in terms of collision, reliability, delay and throughput via extending the CCH interval when the vehicle density is lower than the threshold  $D_{Threshold}$ . As depicted in Fig. 4.5, the threshold  $D_{Threshold}$  is the point at which the network is becoming saturated for the whole synchronisation interval ( $T_{CCH} = 100ms$ ). The evaluation results indicate that the 802.11p MAC protocol is able to satisfy the latency requirement (less than  $100ms$ ). However, it is still very challenging in terms of message delivery reliability. The number of vehicles that can be accommodated in a network is derived and indicated in Table 4.2, in which the setting of  $T_{CCH} = 100ms$  is

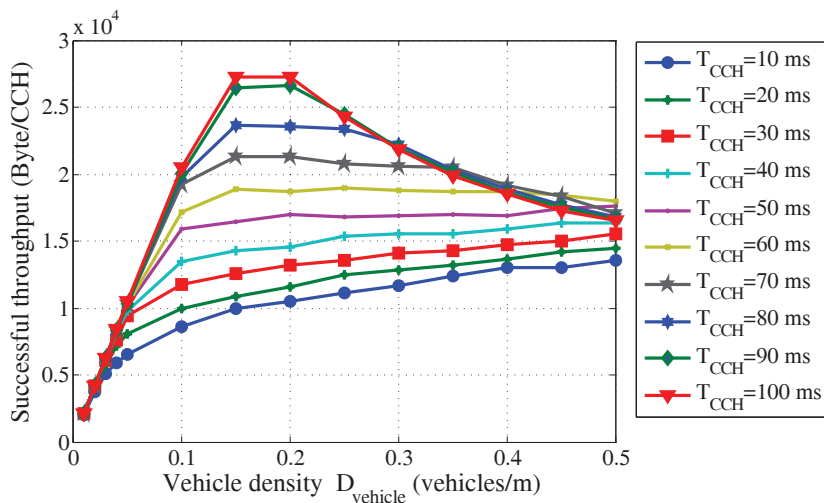


Fig. 4.6 Successful throughput

a particular condition under which the safety messages are delivered in a special safety channel as presented in [MO]. The  $50ms$  CCH interval setting is not appropriate for a network that has a very low or high vehicle density. The 802.11p MAC would perform better if the CCH interval could be adjusted according to the vehicle density.

### 4.2.3 Discussion

In this section, a simulation based evaluation of the IEEE 802.11p MAC protocol in VANET safety applications is proposed. The 802.11p MAC protocol was evaluated in terms of collision, reliability, delay and throughput in the OMNeT++ network simulator. The evaluation covered various vehicle densities ( $0.01-0.5$  vehicles/m) and CCH interval ( $10-100ms$ ) settings. The evaluation results indicate that: (i) the performance of the IEEE 802.11p MAC protocol can be improved via extending the CCH interval; (ii) the IEEE 802.11p MAC protocol can satisfy the latency requirement in VANET safety applications; (iii) the delivery reliability is still very challenging due to the high number of collisions, even considering delivering the safety messages by means of a special safety channel. In addition, the number of vehicles that can be accommodated in a network is also proposed according to the reliability requirement in VANET safety applications.

## 4.3 Performance Evaluation on Veins

In this section, the performance of the IEEE 802.11p MAC protocol in safety applications is re-evaluated based on the Veins framework. In the former section, the evaluation was done without considering the CCH/SCH switching due to the simulation model's limitations. In this section, the performance was re-evaluated with a more realistic simulation setting in order to obtain a more realistic CCH interval adjustment threshold. In contrast to the simulation presented in the former section, only the delay and reliability are focused on in this section.

### 4.3.1 Evaluation Configurations

In order to build a more accurate and realistic simulation model, the latest version of Veins that has been released, 2.0-rc2, [32], was adopted; it is based on MiXiM 2.2 [45] working on the OMNeT++ [62] platform and features the new models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE protocols. In Veins 2.0-rc2, the HCF Back-off process [12], WSM application [160] and CCH/SCH switching function are all properly dealt with.

In the simulations conducted, as illustrated in Fig. 4.7, an bi-directional highway segment of length  $2000m$  is considered. A number of vehicles varying from 10 to 100 are

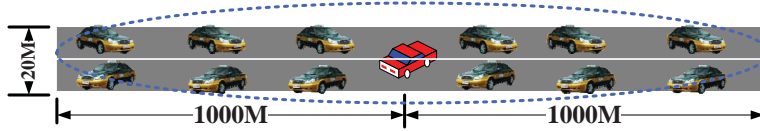


Fig. 4.7 Simulation network

randomly deployed on the highway. The speeds of the vehicles range from 60 to 120K-*m/h*. Each vehicle will return once it reaches the border of the field in order to make sure that every vehicle remains in this highway segment. In this scenario, assume a vehicle (the red vehicle) is stopped right at the middle of this segment due to an accident. The said vehicle involved in the accident broadcasts one emergency message every 100*ms* in AC3. Each of the other vehicles sends one status safety message every 100*ms* in AC0. The safety messages are generated randomly during  $[0, T_{CCH}]$  for each vehicle, where  $T_{CCH}$  denotes the CCH interval. The  $T_{CCH}$  is set as  $[20, 30, 40, 50, 60, 70, 80, 90, 100]$  respectively in order to evaluate the performance of 802.11p MAC at various CCH intervals. As defined in [11], the message size for the BSM part I is 39 bytes while Part II, the Vehicle Safety Extension frame of the BSM, is less than 100 bytes. Hence, the emergency and status safety message sizes are set as 139 bytes (100+39) and 39 bytes respectively. The communication range  $R$  is set as 1000*m* since the expected radio range for a highway is up to 1000*m* [50]. The values of the parameters used in the simulation are depicted in Table 4.3.

### 4.3.2 Evaluation Results

Fig. 4.8 depicts the average status safety message delivery delay for various contention vehicles and CCH intervals. It can be observed that the delay increases according to the increase in number of contention vehicles and a decrease of the CCH interval. The delivery delay  $T_{Delay}$  is the time duration from when the safety message is generated till the time that the message is received by a vehicle. The  $T_{Delay}$  is determined as

$$T_{Delay} = \frac{S_{Status} + S_{MAC}}{R_{Data}} + T_{Queue} + T_{Back-off} + \delta, \quad (4.1)$$

where  $\delta$  is the propagation delay, and  $T_{Queue}$  and  $T_{Back-off}$  denote the Queue time and Back-off time respectively. It can be observed that the  $T_{Delay}$  is mostly determined by  $T_{Queue}$  and  $T_{Back-off}$  since the other parameters, such as  $S_{Status}$ ,  $S_{MAC}$  and  $R_{Data}$ , are constant.  $\delta$  is also an approximate constant in this short range communication scenario. The increase in numbers of contention vehicles as well as the decrease in the CCH intervals will cause more contention together with a longer Queue and Back-off time. As a result, a lengthier delay is caused.

Fig. 4.9 illustrates the average emergency safety message delivery delay for various

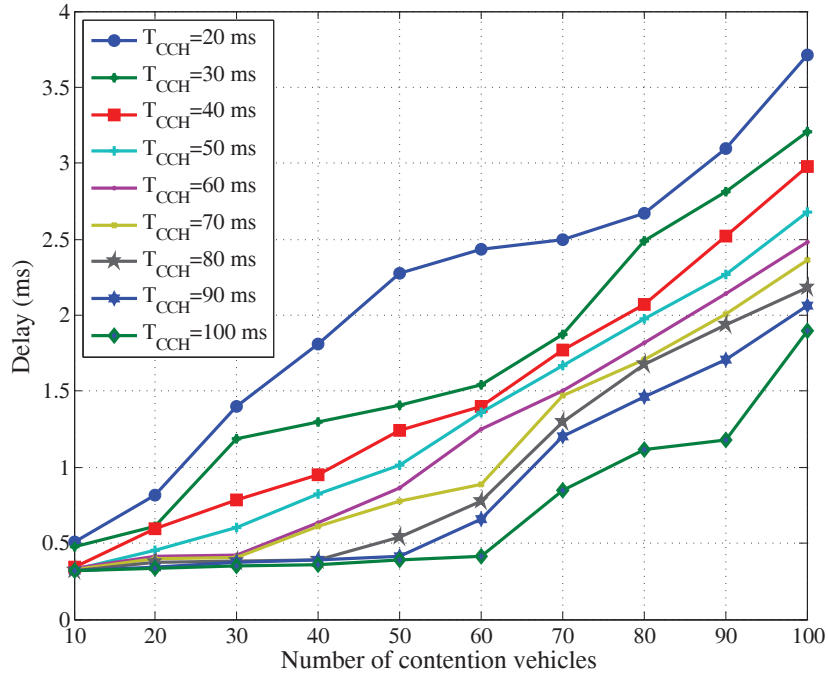


Fig. 4.8 Delay of status message

contention vehicles and CCH intervals. It can be observed that the delay does not change greatly according to the contention vehicles and CCH intervals. Since only one emergency safety message is broadcast every CCH intervals in AC3, neither the contention

Table 4.3 Parameter settings.

Parameter	Value
Status safety message access Class AC	AC0
Emergency safety message access Class AC	AC3
aSlotTime	13 $\mu$ s
Size of emergency safety message $S_{Emergency}$	140bytes
Size of status safety message $S_{Status}$	39 bytes
Size of MAC header $S_{MAC}$	32 bytes
Data rate $R_{data}$	6 Mbps
Communication range $R$	1000 m
Maximum Back-off time $k$	5
Message sending frequency	10/s
Simulation time	10 s
Maximum transmission power	760 mw
Sensitivity	-82dBm
Mobility model	LinearMobility
Propagation model	SimplePathlossModel

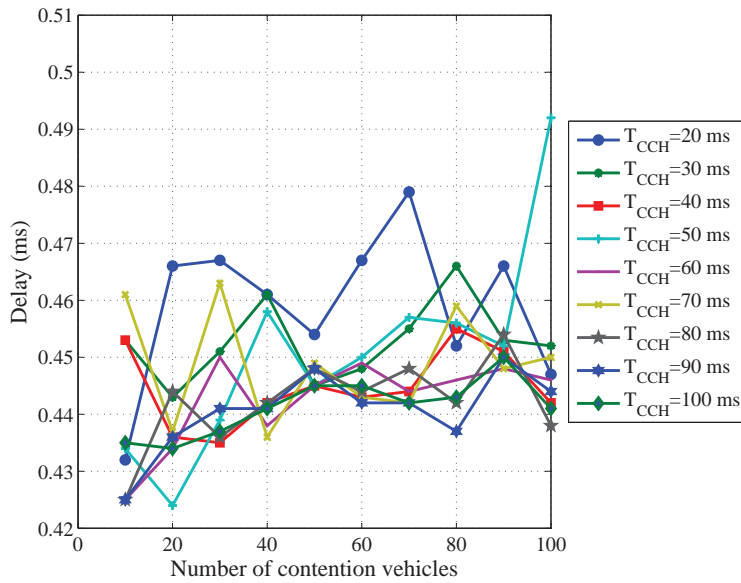


Fig. 4.9 Delay of emergency message

vehicles nor the CCH interval affect the delay significantly. The delay is quite short and stable since the emergency safety message, which is transmitted in AC3, always has the highest priority in accessing a channel.

Fig. 4.10 portrays the average status of the delivery reliability of safety messages for various contention vehicles and CCH intervals. It may be observed that the reliability decreases according to an increase in numbers of contention vehicles and a decrease in CCH intervals. The reliability is strongly related to the collision probability. Since each

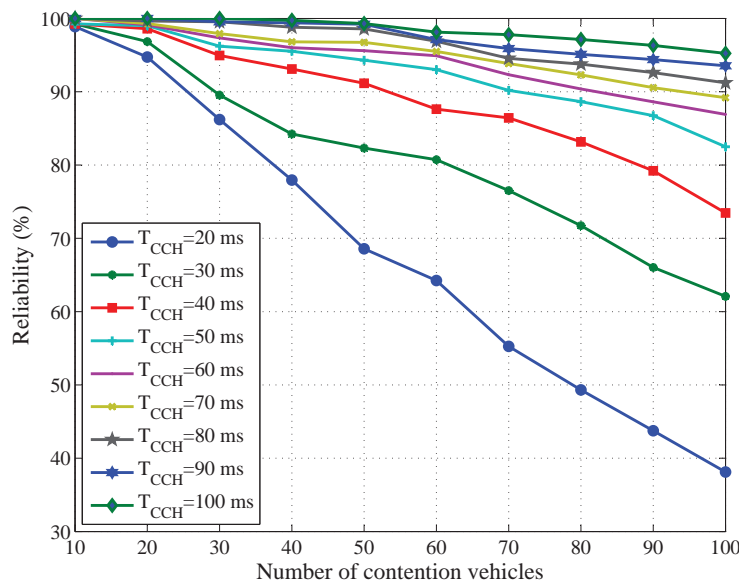


Fig. 4.10 Reliability of status message



Table 4.4 Accommodated number of vehicles on Veins

$T_{CCH}(ms)$	20	30	40	50	60	70	80	90	100
Vehicles ( $P_{Reliability} \geq 99\%$ )	5	10	15	20	25	30	35	40	50
Vehicles ( $P_{Reliability} \geq 95\%$ )	20	25	30	40	50	60	70	80	100

vehicle sends one status safety message every CCH interval, the increase in contention vehicles means that more vehicles will contend for the idle slots. As a result, more collisions will be caused. The decrease of CCH intervals will also cause more collisions since the total idle slots are decreased. As a result, the probability that more vehicles will contest an idle slot at the same time increases. More collisions will cause lessening reliability. According to the requirements for safety applications in VANETs [59] [60], the delay should be less than  $100ms$ . However the reliability requirement is not defined precisely. In this work, considering a specific reliability requirement, the network capacity represented by the number of vehicles that may be accommodated in a network can be derived from Fig. 4.8 and Fig. 4.10. The results obtained are listed in Table 4.4. It is evident that the reliability is much more critical than the delay. Hence, the reliability constitutes the bottleneck for the IEEE802.11p MAC protocol in meeting the safety application requirements in VANETs. Compared with the results obtained in Section 4.2, it may be observed that the network capacity achieved in this simulation is lower than the previous results. This is because the CCH/SCH switching is considered in the Veins simulation model, and the  $4ms$  guard interval is included in the  $T_{CCH}$ . As defined in [12], no message should be transmitted during the guard interval. However, in our previous simulation in Section 4.2, the guard interval is not considered. As a result, the network capacity obtained in this simulation is less than our previous result in Table 4.2.

Fig. 4.11 indicates the average delivery reliability of emergency safety messages for various contention vehicles and CCH intervals. It can be observed that the reliability decreases according to any increase in contention vehicles and decrease in CCH intervals. As previously discussed, the reliability is closely related to the collision probability. Although there is only one emergency transmitted for every CCH interval, the probability of collision owing to the status safety message will increase according to an increase in contention vehicles and a decrease in CCH intervals. As a result, more collisions cause worse reliability. However, the emergency safety messages' delivery reliability is always 100% for the scenarios presented in Table 4.4.

In conclusion, in VANET's safety applications, the CCH interval may be adjusted according to the number of contention vehicles in order to improve the channel utilisation ratio. In the meantime, the safety application requirement should be satisfied since the safety application is critical in VANETs. In the next section, a CCH adaptive algorithm is proposed to consider adjusting the CCH interval.



## 4.4 CCH Adaptive Algorithm

In the former section, it was concluded that the channel utilisation ratio could be improved by adjusting the CCH interval with guaranteed reliability. In this section, a CCH adaptive algorithm is proposed, in which the CCH interval is adjusted according to the number of contention vehicles.

### 4.4.1 Proposed Algorithm

As indicated in Fig. 4.12, the basic concept of the proposed algorithm in this work is to adjust the CCH interval parameter according to the average number of contention vehicles in a highway segment. The number of contention vehicles is recorded by each RSU and collected at the control centre. According to Table 4.4, the CCH interval parameters are calculated and then distributed to every RSU periodically. In this research study, the CCH interval parameters are updated every 100ms. The proposed algorithm contains three steps: Contention vehicle recording, CCH interval calculating and CCH interval resetting.

#### 4.4.1.1 Contention Vehicle Recording

In this algorithm, the CCH interval is set according to the number of contention vehicles in a VANET. Hence, the contention vehicle number  $N_i$  needs to be recorded by each RSU, where  $N_i$  denotes the number of contention vehicles recorded by the  $RSU_i$  during one CCH interval. In this scheme, each RSU records the number of vehicles according to the safety messages received for each cycle. The detail of the contention vehicle

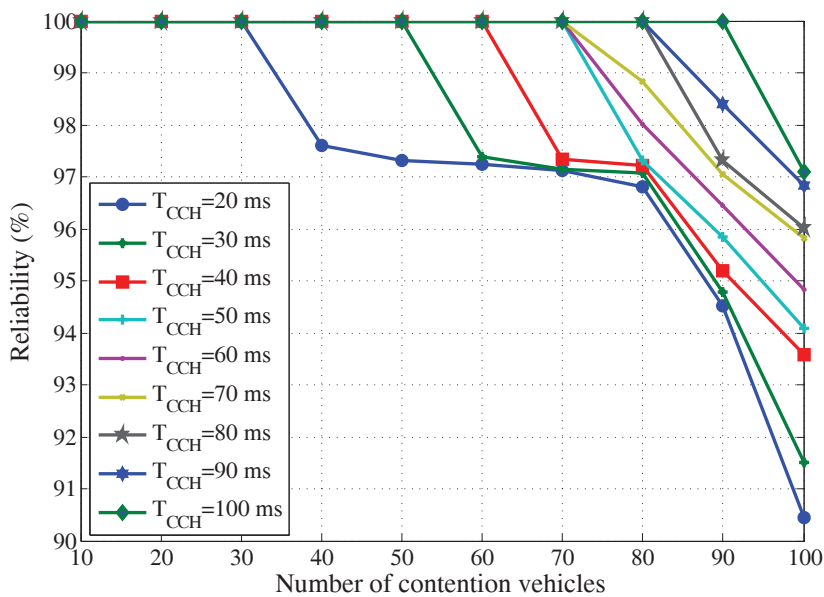


Fig. 4.11 Reliability of emergency message

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**Algorithm 1** Contention vehicle recording algorithm

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- 1: switch to CCH interval
  - 2:  $N_i \leftarrow$  the number of contention vehicles 0
  - 3: **if** received a safety message successfully **then**
  - 4:    $N_i = N_i + 1$
  - 5: **else if** failed to receive a message due to collision **then**
  - 6:    $N_i = N_i + 2$
  - 7: **end if**
  - 8: switch to SCH interval
  - 9: send  $N_i$  to upper layer
- 

recording algorithm is shown in Algorithm. 1. In order to simplify the algorithm, the collision is assumed to occur only between two vehicles. As a result, the number of contention vehicles is recorded as 2 for a collision. The  $N_i$  will be finally sent to the control centre in order to calculate the proper CCH interval parameter according to the average number of contention vehicles in a highway segment.

**4.4.1.2 CCH Interval Calculating**

In this algorithm, as portrayed in Fig. 4.12, the control centre is responsible for calculating the CCH interval according to the number of contention vehicles. As discussed in the former section, the  $N_i$  recorded by  $RSU_i$  for each CCH interval is periodically collected in the control centre. Suppose that a highway segment contains  $j$  RSUs; the average number of contention vehicles  $N_{Ave}$  can then be determined as

$$N_{Ave} = \frac{1}{j} \times \sum_{i=1}^j N_i. \tag{4.2}$$

The CCH interval parameter  $T_{CCH}$  can then be determined according to  $N_{Ave}$  and Table 4.4. Suppose the reliability requirement is 95%; the details of the CCH interval calculating algorithm are shown in Algorithm. 2

**4.4.1.3 CCH Interval Resetting**

As stated in [160], in WAVE, each vehicle is expected to join a WBSS, which is a unique identifier for each communication zone. Vehicles must associate with only one WBSS

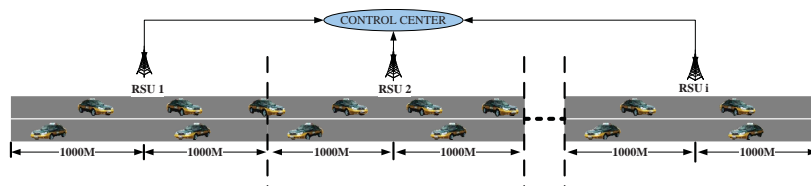


Fig. 4.12 CCH interval adaptive example

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**Algorithm 2** CCH interval calculating algorithm

---

```
1:  $N \leftarrow 0$ 
2:  $N_{Ave} \leftarrow 0$ 
3:  $j \leftarrow$  the number of RSUs
4: for  $i = 1; i \leq j; i++$  do
5:   receive  $N_i$  from  $RSU_i$ 
6:    $N = N + N_i$ 
7: end for
8:  $N_{Ave} = \frac{N}{j}$ 
9: if  $N_{Ave} \leq 20$  then
10:   $T_{CCH} = 20$ 
11: else if  $20 < N_{Ave} \leq 25$  then
12:   $T_{CCH} = 30$ 
13: else if  $25 < N_{Ave} \leq 30$  then
14:   $T_{CCH} = 40$ 
15: else if  $30 < N_{Ave} \leq 40$  then
16:   $T_{CCH} = 50$ 
17: else if  $40 < N_{Ave} \leq 50$  then
18:   $T_{CCH} = 60$ 
19: else if  $50 < N_{Ave} \leq 60$  then
20:   $T_{CCH} = 70$ 
21: else if  $60 < N_{Ave} \leq 70$  then
22:   $T_{CCH} = 80$ 
23: else if  $70 < N_{Ave} \leq 80$  then
24:   $T_{CCH} = 90$ 
25: else if  $N_{Ave} > 80$  then
26:   $T_{CCH} = 100$ 
27: end if
28: broadcast  $T_{CCH}$  to all RSUs
```

---

at a time. To establish a WBSS, an RSU periodically broadcasts the WSA on the CCH. WSA contains the necessary information for the users to join the WBSS, such as the WBSS identifier, the availability of a service, the selected SCH, synchronisation timing information etc. In the meantime, all the vehicles have to listen to the CCH during the CCH intervals. In our proposed CCH adaptive algorithm, the WSA is extended to contain a CCH interval parameter  $T_{CCH}$ . The  $T_{CCH}$  is calculated by the control centre and distributed to every RSU every 100ms. Each vehicle will reset its CCH interval according to the  $T_{CCH}$  contained in WSA. However, the new CCH interval parameter will be activated during the next cycle, since the vehicle is already on a CCH channel. The detail of the CCH interval resetting algorithm is depicted in Algorithm. 3.

### 4.4.2 Validation and Discussions

The proposed CCH adaptive algorithm is evaluated utilising the same simulation configuration as discussed in Section 4.3.1. The CCH adaptive algorithm is evaluated for two reliability requirement settings respectively. As discussed in Section 4.3.2, for emergency messages, the delay is quite short and stable. In addition, the reliability is always 100% for the scenario in Table 4.4. Hence, only the status messages are discussed in this section.

Fig. 4.13 illustrates the CCH interval settings for various contention vehicles. In the IEEE 802.11p, the CCH interval is a constant with  $50ms$ . In the proposed CCH adaptive algorithm, the CCH interval is adjusted according to the number of contention vehicles in a network. According to Table 4.4, the CCH adjusting thresholds are different for different reliability requirements. It can be observed that the CCH interval for the adaptive algorithm increases according to the number of contention vehicles in order to meet the reliability requirement. In the scenario where the network density is low, a shorter CCH interval ( $< 50ms$ ) is sufficient for the status safety messages to meet a certain reliability requirement. As a result, a longer SCH interval ( $> 50ms$ ) is obtained to offer a better service to the customer. On the other hand, in the scenario where the network density is high, the network needs a longer ( $> 50ms$ ) CCH interval to deliver the status safety messages in order to meet the reliability requirement.

Fig. 4.14 depicts the average delivery reliability status of safety messages for various contention vehicles. It can be observed that the CCH adaptive algorithm outperforms the 802.11p in terms of reliability when the number of contention vehicles is greater than a specific threshold. The threshold is  $N_{Threshold} = 15$  and  $N_{Threshold} = 30$  for the two reliability requirements ( $\geq 99\%$  and  $\geq 95\%$ ) respectively. On the other hand, the 802.11p outperforms the CCH adaptive algorithm in terms of reliability when the number of contention vehicles is less than the threshold  $N_{Threshold}$ . It should be noted that the threshold  $N_{Threshold}$  is just the point that the  $T_{CCH}$  is switching to be  $50ms$  according to Table 4.4. However, the reliability of the CCH adaptive algorithm is always better than the reliability requirement when the number of contention vehicles does not exceed the maximum network capacity  $N_{Max}$ , which is  $N_{Max} = 55$  and  $N_{Max} = 100$  for the two reliability requirements ( $\geq 99\%$  and  $\geq 95\%$ ) respectively.

---

#### Algorithm 3 CCH interval resetting algorithm

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- 1: start timer  $t \leftarrow T_{CCH}$
  - 2: receive a WSA
  - 3:  $T_{CCH} \leftarrow CCH$  interval parameter in WSA
  - 4: **if**  $t=0$  **then**
  - 5: switch to SCH
  - 6: **end if**
-

In Fig. 4.15, the average status safety message delivery delay for various contention vehicles is illustrated. It can be observed that the delay shows a similar distribution to that of the reliability. The CCH adaptive algorithm records a slightly longer delay than the 802.11p when the number of contention vehicles is less than the threshold  $N_{Threshold} = 15$  and  $N_{Threshold} = 30$  for the two reliability requirements ( $\geq 99\%$  and  $\geq 95\%$ ) respectively. On the other hand, the CCH adaptive algorithm exhibits a slightly shorter delay than the 802.11p when the number of contention vehicles is greater than the threshold  $N_{Threshold}$ . It can also be observed that all the delays are much briefer than the latency requirement ( $< 100ms$ ).

In conclusion, the CCH adaptive algorithm can improve the channel utilisation ratio for a low traffic scenario (up to 60%) and increase its reliability for a heavy traffic scenario via adjusting the CCH interval. In the meantime, the average delivery delay is much shorter than the latency requirement in the scenarios considered.

## 4.5 Conclusion

In this chapter, the IEEE 802.11p MAC protocol is evaluated based on the INET and Veins frameworks, respectively. The important metrics of QoS, such as collision, reliability, throughput, delays and network capacity are evaluated and discussed. From the evaluation results it may be concluded that the performance of the IEEE 802.11p MAC protocol can be improved by means of extending the CCH interval. A CCH adaptive

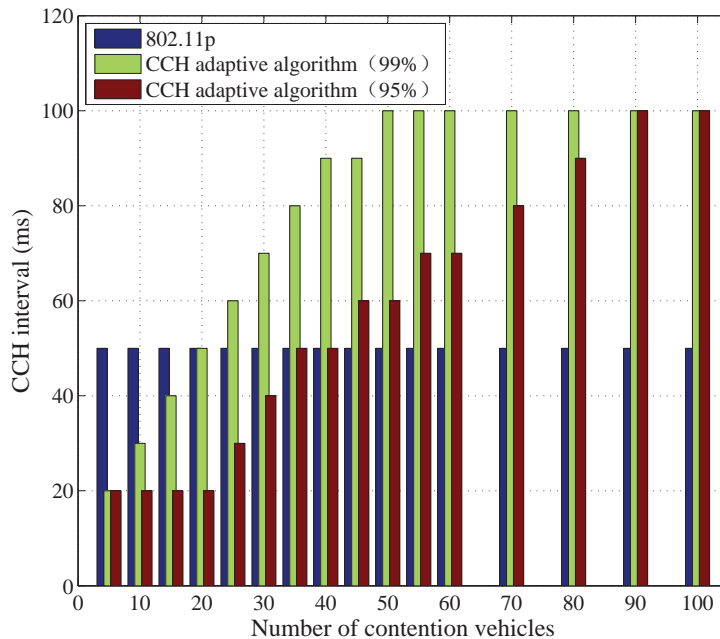


Fig. 4.13 CCH interval

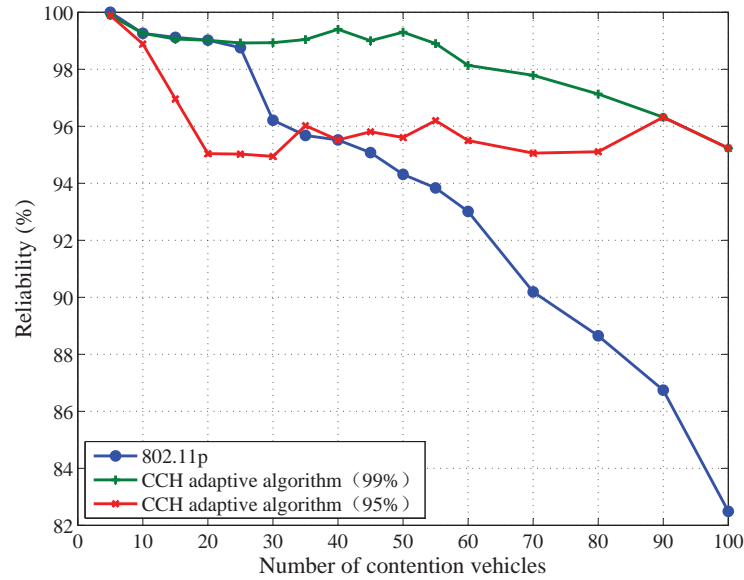


Fig. 4.14 Reliability of status message

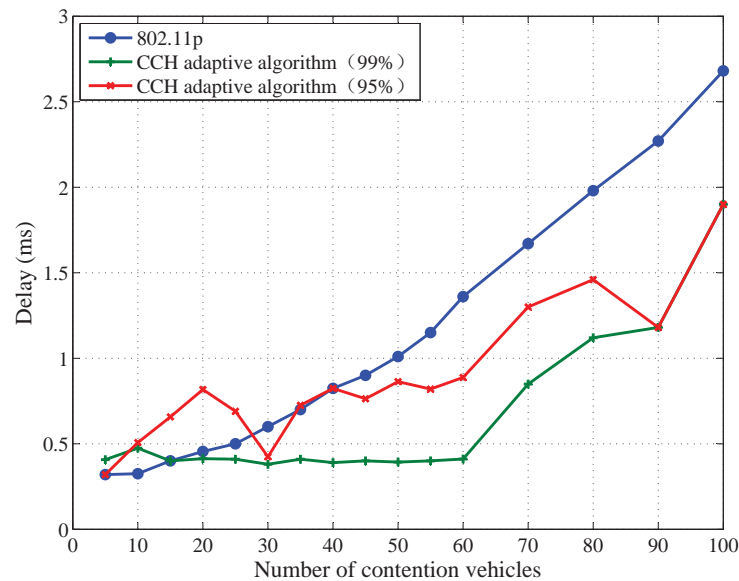


Fig. 4.15 Delay

algorithm for the IEEE 802.11p MAC protocol is then proposed, in which the CCH interval is adjusted according to the average number of contention vehicles in a VANET. In comparison with the existing works in [46] [65] [63], the safety application's reliability, rather than that of the SCH service, is considered and guaranteed with a higher priority. The network capacity with a certain reliability requirement is derived, which is taken as the CCH adjustment threshold in the CCH adaptive algorithm. The simulation results demonstrate that the CCH adaptive algorithm can improve the channel utilisation ratio (up to 60%) for a low traffic scenario and increase the reliability for a heavy traffic

## **Evaluation and Enhancement of 802.11p CCH**

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scenario via adjusting the CCH interval.

In this chapter, consideration is given solely to the CCH of 802.11p. The evaluation and enhancement of 802.11p on SCH are examined and discussed in the following chapter.

# Chapter 5

## Evaluation and Enhancement of 802.11p SCH

### 5.1 Introduction

In this chapter, the evaluation and enhancement of 802.11p on SCH are studied and discussed. Many researchers have focused on the CCH since the safety related messages are designed to broadcast on CCH. By comparison, the SCH has not received much attention. In SCH, the service capacity and the performance with diverse numbers of contention vehicles is very important to the designing of VANETs. In [38] [39] and [63], the performances of 802.11p MAC for SCH are evaluated with a fixed SCH interval under saturated conditions. In [47] and [20], the effects of time allocations on CCH and SCH in IEEE 802.11p are described. However, the performance evaluations are focused on CCH instead of SCH. In this chapter, the performance of 802.11p MAC, with various SCH interval settings, is evaluated first: i.e. the throughput, latency and channel utilisation for different ACs will be evaluated. Secondly, a multi-SCH algorithm considering two service channels is proposed and discussed. The proposed multi-SCH algorithm will balance the traffic load according to the channel's utilisation.

The remainder of this chapter is organised as follows: In Section 5.2, the 802.11p is evaluated based on a simulation environment where the evaluation covers both contention and contention free scenarios and the evaluation results are thereafter analysed and discussed. The proposed multi-SCH algorithm is then explored and evaluated in Section 5.3. Finally, the conclusions are given in Section 5.4.

### 5.2 Performance Evaluation

As stated above, the performance of the IEEE 802.11p MAC protocol on SCH is evaluated based on simulation. The performance of different ACs with various SCH intervals



Table 5.1 Variables List

Variable	Description
$S_{message}$	Size of service message
$S_{MAC}$	Size of MAC header
$S_{PHY}$	Size of PHY header
$T_{guard}$	Guard interval
$T_{SCH}$	SCH interval
$T_{slot}$	Slot interval
$T_{AIFS}$	AIFS interval
$T_{tran}$	Transmission duration
$\beta$	Bitrate
$\tau$	Throughput
$\tau_{suc}$	Successful throughput
$P_{reliability}$	Delivery reliability
$R_{sent}$	Sent ratio
$n_{total}$	Number of total messages generated
$n_{sent}$	Number of messages sent
$n_{rev}$	Number of messages received
$T_{Latency}$	Transmission latency
$R_{busy}$	Channel busy ratio
$T_{busy}$	Channel busy time

is discussed. All the variables defined and used in this section are listed in Table 5.1. According to the IEEE 802.11p [12] and IEEE 1609 standards [14], the values of some key variables are set as shown in Table 5.2. The message size  $S_{MAC}$  is set to 500 bytes for all traffic classes, in accordance with the guidelines from [58].

Table 5.2 Variables settings

Variable	Value
$S_{message}$	500 bytes
$S_{MAC}$	32 bytes
$S_{PHY}$	8 bytes
$T_{guard}$	4ms
$T_{slot}$	13 $\mu$ s
$\beta$	6Mbits/s
aSIFSTime	32 $\mu$ s

### 5.2.1 Evaluation Configurations

The Veins 2.0 [32] is also used in this section. In the simulations conducted, as shown in Fig. 5.1, a bi-directional highway segment of length  $1000m$  is considered. A number of vehicles varying from 20 to 200 are deployed on the highway randomly. The speeds of the vehicles range from 60 to  $120Km/h$ . Each vehicle will return once it reaches the border of the field in order to make sure that every vehicle remains in this highway segment. Two simulation scenarios are considered in this study. The first scenario is contention free, in which only one vehicle is sending traffic flow on a single AC for each round simulation. The traffic flow is generated during  $[0, T_{SCH}]$  with a 500 bytes message size and a  $0.6ms$  arrival interval. The  $0.6ms$  arrival interval is set in order to ensure that there are always some messages waiting in the queue to simulate a saturated network environment for each AC. The transmission duration for one message is determined as

$$T_{tran} = \frac{S_{message} + S_{MAC} + S_{PHY}}{\beta}. \quad (5.1)$$

As referred to in Table 5.2, the  $S_{MAC}$  is 32 bytes, while the data rate  $\beta$  is  $6Mbits/s$ . The transmission duration for a message may then be calculated which is  $T_{tran} = 0.7ms$ . Hence, the  $0.6ms$  arrival interval can guarantee that there are always some messages waiting in the queue. The  $T_{SCH}$  is set as  $[10, 20, 30, 40, 50, 60, 70, 80, 90, 100]$  respectively in order to evaluate the performance of 802.11p MAC with various SCH intervals. Under these conditions, the maximum throughput for every single AC with various SCH intervals will be obtained.

The second scenario is a contention scenario. In this scenario, the vehicles are divided into four equal groups. The traffic flow is generated during  $[0, T_{SCH}]$ . The traffic flow defined in [39] is adopted with some modification in this work. In [39], four traffic categories were defined as follows: 1) high-priority audio flow (64 kb/s); 2) H.263 video flow (64 kb/s) with medium priority; 3) best effort (128 kb/s) with low priority; and 4) background traffic (256 kb/s) with the lowest priority. Using these definitions, the performance of four ACs cannot be compared since the traffic flow for different ACs is different. Hence, in this work, the traffic flows for different ACs are set to be equal. The traffic flow is depicted in Table 5.3. The  $T_{SCH}$  is also set as  $[10, 20, 30, 40, 50, 60, 70, 80, 90, 100]$  respectively in order to cover the various SCH intervals. The communication range  $R$

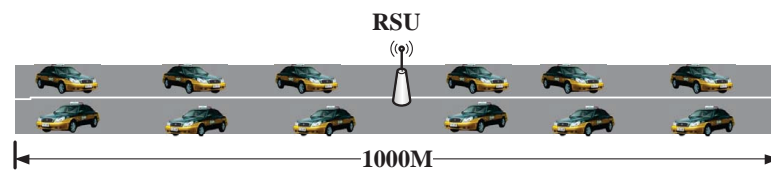


Fig. 5.1 Simulation network

Table 5.3 Description of traffic flows.

	VoIP	Video	Best effort	Background
AC	AC0	AC1	AC2	AC3
Packet size	500 bytes	500 bytes	500 bytes	500 bytes
Data rate $R_{Data}$	64 kbits/s	64 kbits/s	64 kbits/s	64 kbits/s
Vehicles	Group 1	Group 2	Group 3	Group 4

is set as  $1000m$  since the expected radio range for a highway is up to  $1000m$  [50]. The values of parameters used in simulations are depicted in Table 5.4.

Table 5.4 Simulation settings.

Parameter	Value
Communication range $R$	1000 m
Maximum Back-off time $k$	5
Simulation time	10 s
Maximum transmission power	760 mw
sensitivity	-82dBm
Propagation model	SimplePathlossModel

## 5.2.2 Evaluation Results

### 5.2.2.1 Contention Free Scenario

In the contention free scenario, only one vehicle is sending messages on an AC. Hence, there will be no collisions. In this study, the various SCH intervals are considered. The throughput on SCH for one second will be affected by the different SCH interval settings. Hence, the throughput for one  $100ms$  synchronisation interval cycle rather than one second is considered. According to the scheme of 802.11p MAC protocol, the channel needs to be idle for  $T_{AIFS}$  before AC can access the channel. The  $T_{AIFS}$  is determined as

$$T_{AIFS} = aSIFSTime + AIFSN * T_{slot}. \quad (5.2)$$

The message that can be transmitted during one cycle can then be determined as

$$n = \frac{T_{SCH} - T_{guard}}{T_{AIFS} + T_{tran}}. \quad (5.3)$$

The message will not be sent if there is not enough time left until the switching of the channel for this SCH interval. The exact number of messages that can be sent during a SCH interval is determined as  $n' = \lfloor n \rfloor$ . The throughput for each cycle can be determined

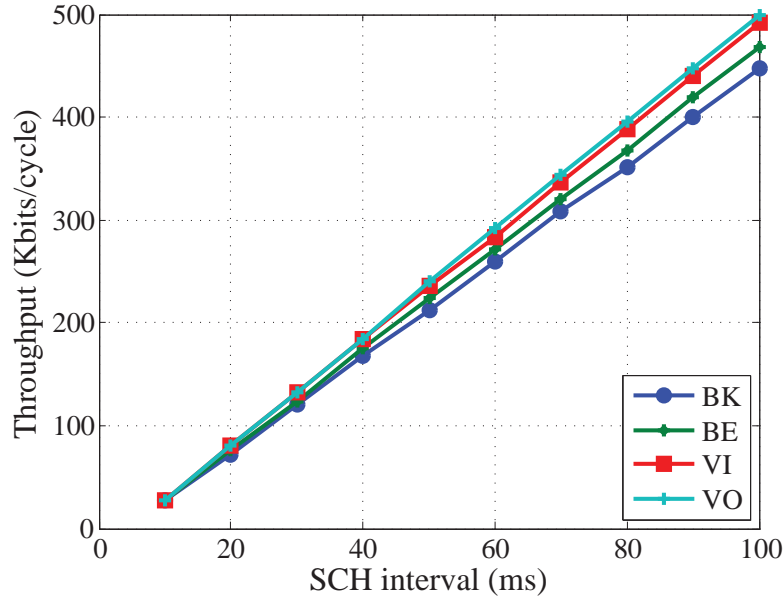


Fig. 5.2 Throughput in theory

as

$$\tau = n' * S_{message}. \quad (5.4)$$

The theory and simulation results of throughput for each AC with various SCH intervals are depicted in Fig. 5.2 and Fig. 5.3 respectively. Compared with the theory and simulation throughput, the results are very similar. The throughput increases following the increase of the SCH interval. The throughput on higher priority AC yields a better result than the lower priority AC. Suppose  $N_{CFuser}$  denotes the maximum users that a network can accommodate under a contention free scenario,  $N_{CFuser}$  can be determined as  $N_{CFuser} = \frac{\tau}{R_{Data}}$ . The maximum service capacities by presence of users that a network can accommodate for various SCH interval settings under a contention free scenario are listed in Table 5.5.

The delivery latency obtained in simulation is shown in Fig. 5.4. The delivery latency  $T_{Latency}$  is the time from when the message is generated till the time that the message is received by a vehicle. It can be seen that the latency decreases following the increase of the SCH interval. The latency is mostly caused by the query time. The longer the

Table 5.5 Service capacity under contention free scenario

$T_{SCH}(ms)$	10	20	30	40	50	60	70	80	90	100
AC0	3	11	18	25	32	39	47	53	61	68
AC1	3	11	19	26	34	41	49	56	64	71
AC2	4	12	20	27	35	43	51	58	67	75
AC3	4	12	20	28	36	44	51	59	67	75

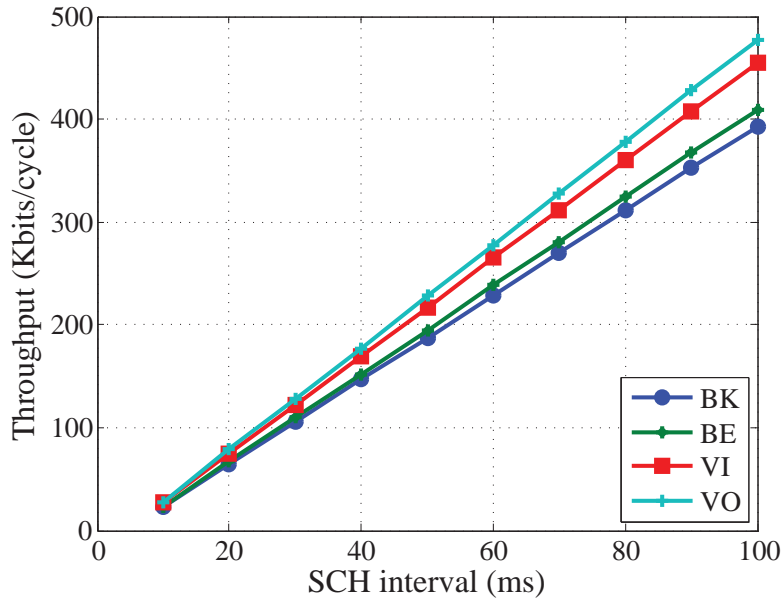


Fig. 5.3 Throughput in simulation

SCH interval is, the shorter the query time will be. As a result, the long SCH interval causes short delivery latency. It can also be noted that the latency on higher priority AC is shorter than the latency on lower priority AC. This is because the higher priority AC has a shorter AIFS value. Hence, with the same SCH interval, more messages can be transmitted due to the shorter AIFS.

In order to study the channel utilization for different ACs, A channel busy ratio is proposed. The channel busy ratio  $R_{busy}$  is determined as  $R_{busy} = \frac{T_{busy}}{T_{SCH}}$ , where  $T_{busy}$  denotes the channel busy time for one SCH interval. The busy ratio obtained in simulation

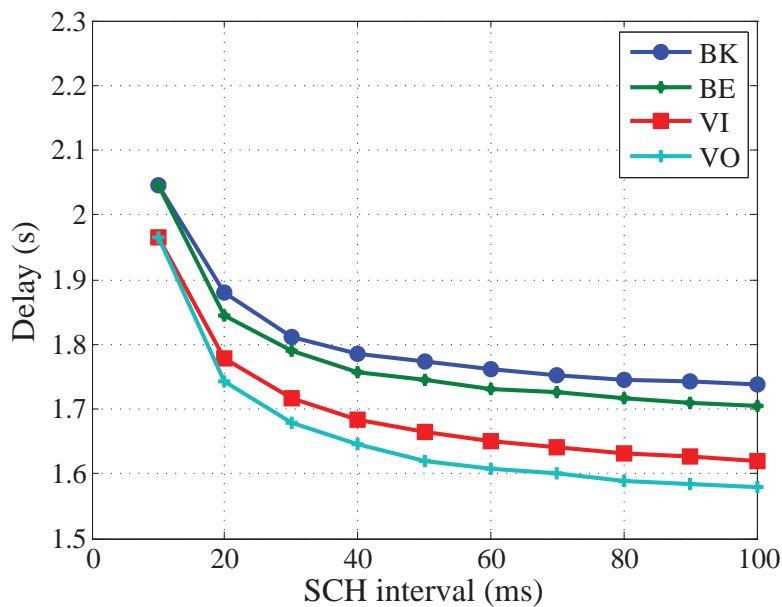


Fig. 5.4 Delivery latency

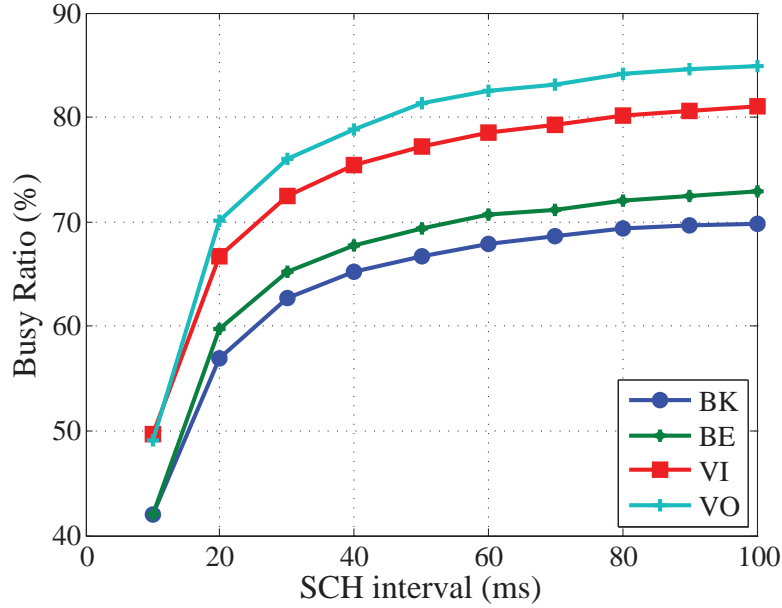


Fig. 5.5 Busy ratio

is illustrated in Fig. 5.5. It can be observed that the higher priority AC has higher channel utilization. This is also because of the different AIFS values for different ACs. The higher priority AC has a shorter AIFS value and consequently higher channel utilization. In addition, the channel busy ratio also increases following the increase of the SCH interval. There are two reasons: (i) the guard interval is included in the SCH interval which affects the busy ratio much when the SCH interval is short. For instance, the busy ratio is less than 50% when the SCH interval is 10ms since the 4ms guard interval cannot be occupied. (ii) The message will not be transmitted if the time left in the current SCH interval is less than the transmission duration. This also affects the busy ratio much when the SCH interval is short.

### 5.2.2.2 Contention Scenario

In order to show the channel access probability for different ACs, a sent ratio  $R_{sent}$  is defined. The  $R_{sent}$  is determined as  $R_{sent} = \frac{n_{sent}}{n_{total}}$ , where the  $n_{sent}$  denotes the number of messages that are able to access the channel and are sent out, while  $n_{total}$  denotes the total number of messages generated in these simulation scenarios. The sent ratio is shown in Fig. 5.6. The SCH interval  $T_{SCH}$  varies from 10 to 100ms, and it can be observed that VO always has the first priority to access the channel, and the sent ratio for VO is always 100%. The sent ratio for the AC (VI, BE and BK) decreases, following the increase in the number of the vehicles. It may be readily understood that the more vehicles there are, the greater the competition will be; as a result, there is less opportunity for the AC (VI, BE and BK) to access the channel. Comparing all the figures in Fig. 5.6, it may be observed that the sent ratio increases following the increase of SCH interval  $T_{SCH}$  until

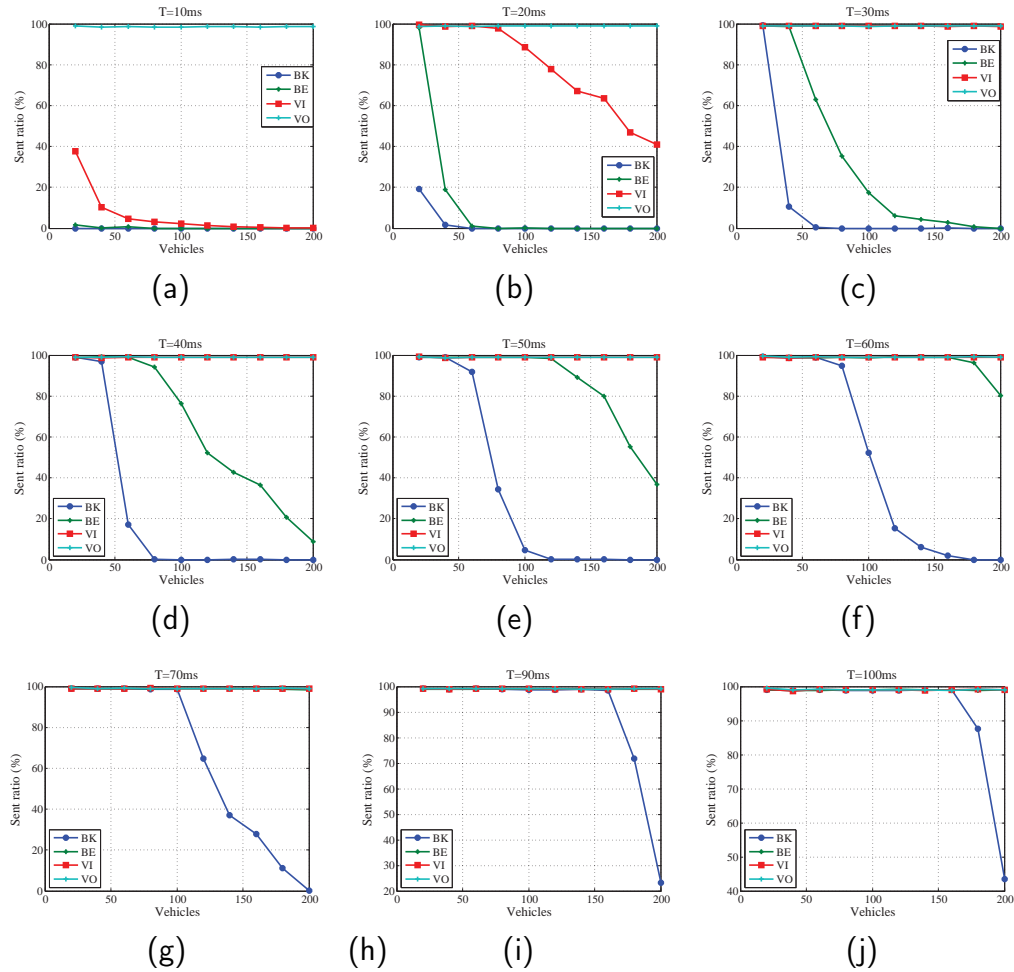


Fig. 5.6 Sent ratio

it reaches 100%. For instance, the sent ratios for VO, VI and BE are always 100% in the simulation scenario when the SCH interval  $T_{SCH}$  is set as  $100ms$ . In the meantime, only the VO in given a 100% sent ratio when the  $T_{SCH}$  is set as  $10ms$ . Hence, it may be concluded that the sent ratio for every AC increases following the increase of the SCH interval and the decrease of the number of vehicles in the communication range.

However, the messages might not be delivered successfully due to the sent ratio and the collisions. In order to find out how much traffic is delivered successfully, delivery reliability  $P_{reliability}$  is proposed, which is determined as  $P_{reliability} = \frac{n_{rev}}{n_{total}}$ . Where the  $n_{rev}$  denotes the number of messages received successfully. The reliability for various SCH intervals is illustrated in Fig. 5.7. It can be observed that the reliability for all ACs is decreasing following the increase of the vehicles. This is because the increased number of vehicles cause more contentions. As a result, the corresponding reliability decreases. When considering the different SCH intervals, it may be observed that the reliability increases following the increase of the SCH interval since the longer interval causes less contention.

Compared to the different ACs, it can be noticed that the reliability of BK and BE

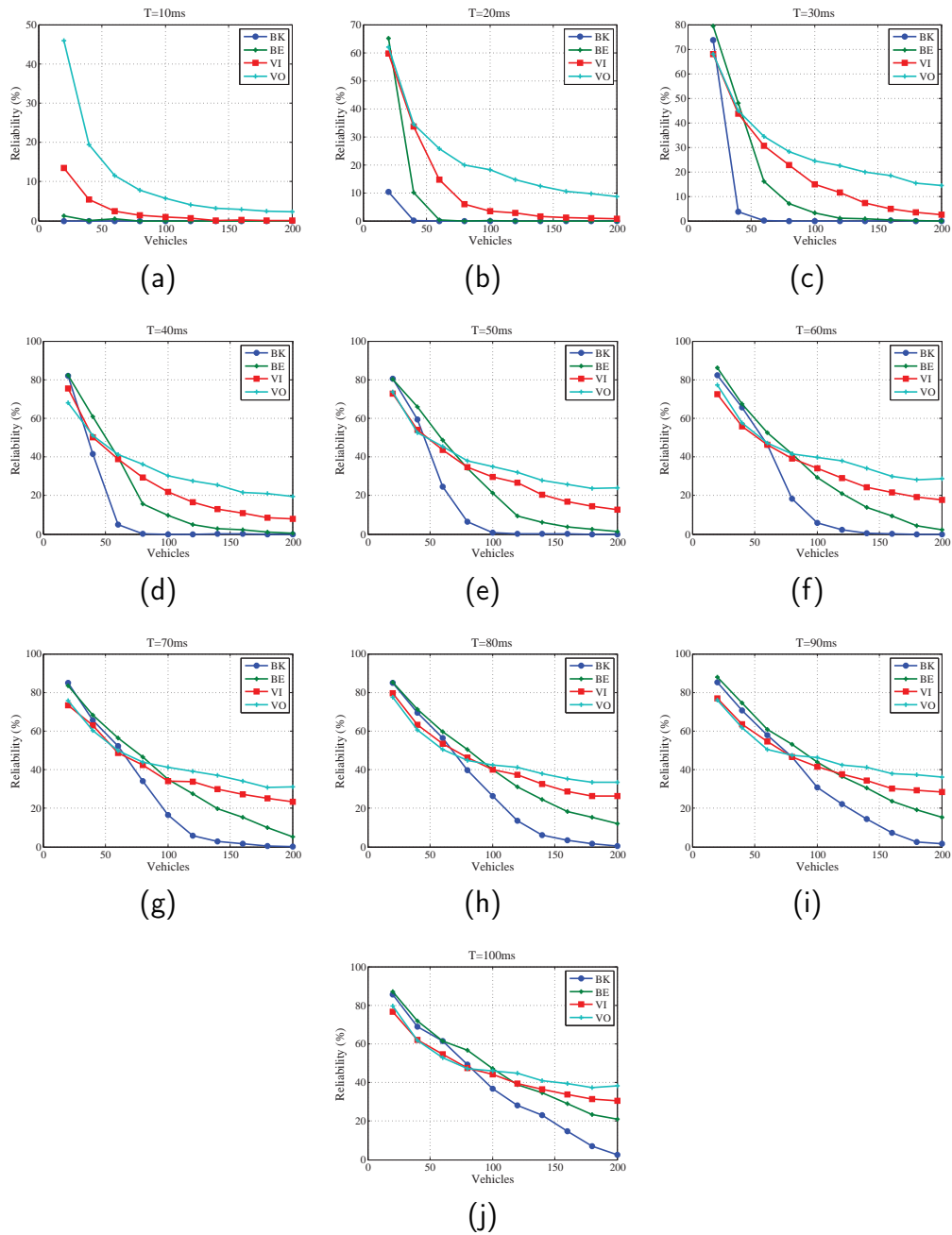


Fig. 5.7 Reliability

is even better than the reliability of VO and VI when the number of vehicles is low. In other words, low priority AC outperforms high priority AC in terms of reliability under the scenario that the contention is low in the channel. This result seems to contradict the initial designing of the different ACs. In order to explain the result, the concept of contention zones presented in [39] is adopted in this study. The contention zones are depicted in Fig. 5.8. In this study, the time slots are divided into four zones. In Zone 1, only VO traffic flows compete for the shared channel. In Zone 2, VO and VI traffic flows compete to access the channel. In Zone 3, VO, VI and BE traffic flows compete for the channel. In Zone 4, all ACs traffic flows can compete for the channel. In this



study, each AC has an equal traffic flows setting. In the scenario when the contention is not high, each message in different ACs has an opportunity to access the channel. Hence, the messages cannot benefit from the high priority AC. On the contrary, the messages with high priority AC have a high collision probability because the collision with VO could happen during Zone 1 to Zone 4. However, the collision with BK can only happen during Zone 4. As a result, the reliability of BK and BE is even better than the reliability of VO and VI when the number of contention vehicles is low. Following the increase of contention vehicles, the advantage of high priority ACs is demonstrated. In a congestion network, VO always outperforms the other ACs in terms of reliability for all SCH interval settings.

Fig. 5.9 depicts the average message delivery latency for each AC with various SCH interval settings. For the BE and BK, these two ACs could have no opportunity to access the channel under certain congestion scenarios. As a result, latency could not be recorded since they never obtain the chance to send out their message. In order to compare the latencies for different ACs and various SCH interval settings, the latencies are set as 3000ms if the AC has not sent any message. It can be observed from Fig. 5.9 that the latency increases following the increase of contention vehicles and a decrease of the SCH interval. The latency for different AC varies greatly since the messages in different ACs have a different queuing time. The messages in low priority AC, such as BE and BK, will be kept waiting for a long time till they are given a chance to access the channel. However, the messages in high priority ACs, such as VO and VI, will access the channel much more rapidly and easily than BE and BK. The BK message never had any chance to access the channel, as shown in Fig. 5.9 (a), when the SCH interval is set as 10ms. The messages in VO always have a very short latency for the simulation scenarios. Hence, it can be seen from the latency results that the 802.11p can guarantee the performance of the latency critical messages transmitted in high priority ACs in terms of latency.

Fig. 5.10 depicts the throughput for each AC with various SCH interval settings. It can be seen that the throughput for VO always increases linearly, following the increase in the number of vehicles. The throughput for VI, BE and BK goes up firstly following the increase of the number of vehicles. The throughput then diminishes due to the decrease of the corresponding sent ratio. The messages on VO can always access the

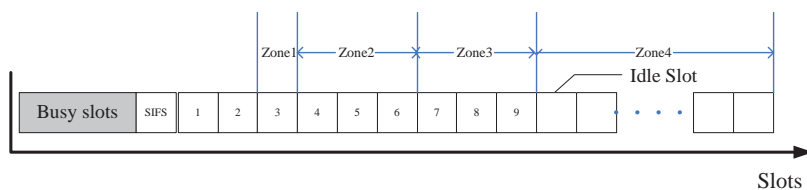


Fig. 5.8 Contention zones

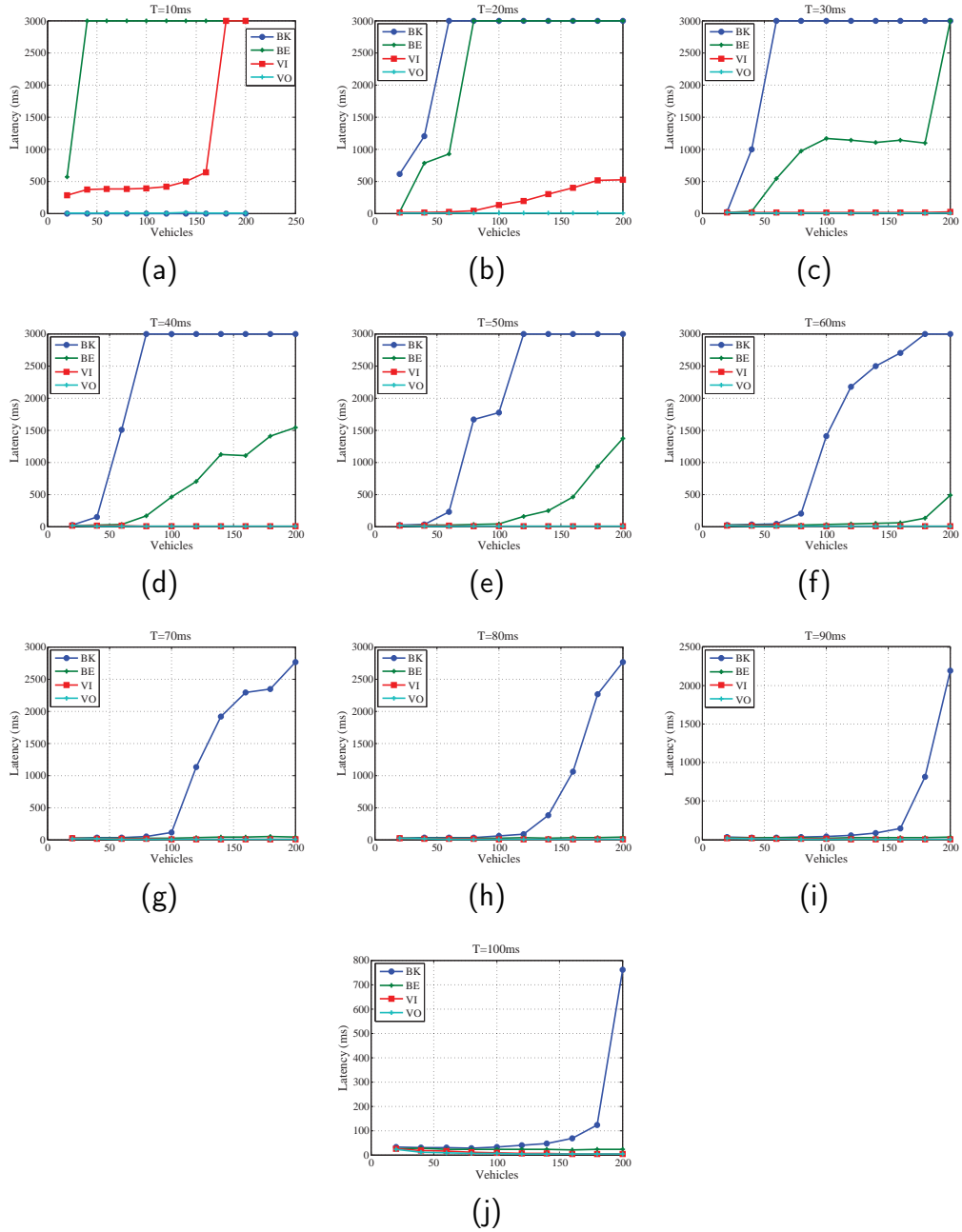


Fig. 5.9 Latency

channel no matter how long the SCH interval is since VO has the first priority to access the channel.

Part of the throughput could be wasted due to the collisions. Hence, this study considers a successful throughput. Here such a throughput is determined as  $\tau_{suc} = n_{rev} * S_{message}$ . The successful throughput for each AC with various SCH interval settings is shown in Fig. 5.11. It can be observed that this throughput increases following the increase of contention vehicles before an apex. After the apex, the said throughput will decrease following the increase in numbers of contention vehicles. The apex is the maximum successful throughput for an AC. After this apex is reached, more contentions

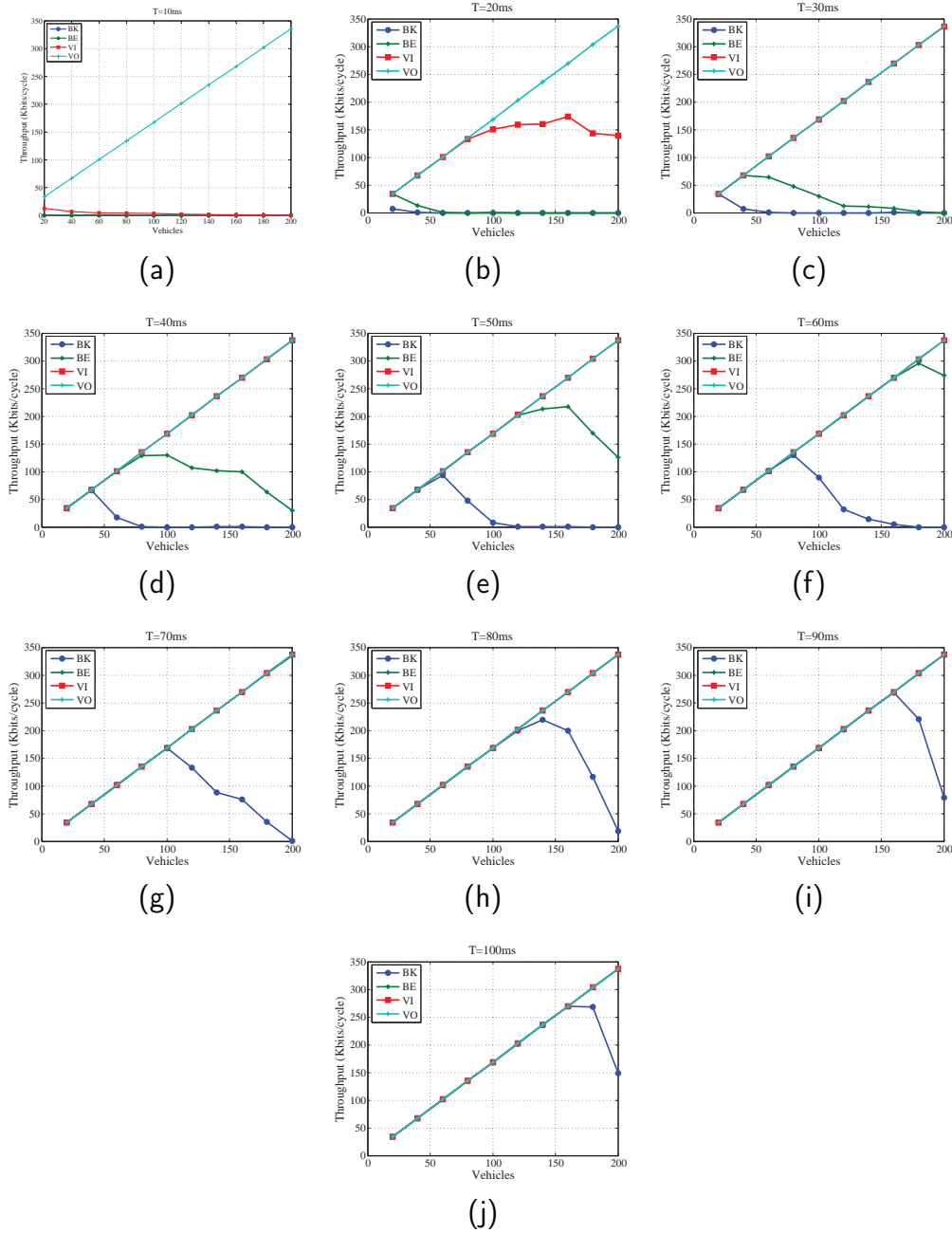


Fig. 5.10 Throughput

will cause more collisions and decrease the successful throughput. The peak points for ACs are different due to the different values of AIFS. The AC with short AIFS will be given more opportunities to access the channel and transmits messages. The advantage of high priority AC can be observed very clearly in a congested network, as shown in Fig 5.11 (a) and (b). The total successful throughput for all ACs is illustrated in Fig. 5.12. It may be observed that there is also a peak point for the total successful throughput with various SCH intervals. Suppose  $N_{Cuser}$  denotes the users which a network is able to accommodate in a contention scenario;  $N_{Cuser}$  can be determined as  $N_{Cuser} = \frac{\tau_{suc}}{\beta}$ . The maximum service capacities by presence of users that a network can accommodate

for various SCH interval settings under a contention scenario are listed in Table 5.6. Compared with the results in Table 5.5, the maximum users in the contention scenario are fewer than the users in the contention-free scenario. This is because the collisions occur under a contention conditions, and some channel durations are wasted due to the collisions. The numbers of contention vehicles when the network achieves the maximum successful throughput are listed in Table 5.7. This can be regarded as the network capacity to achieve the maximum successful throughput. The successful throughput will decrease if the number of vehicles in a network is greater than the network capacity.

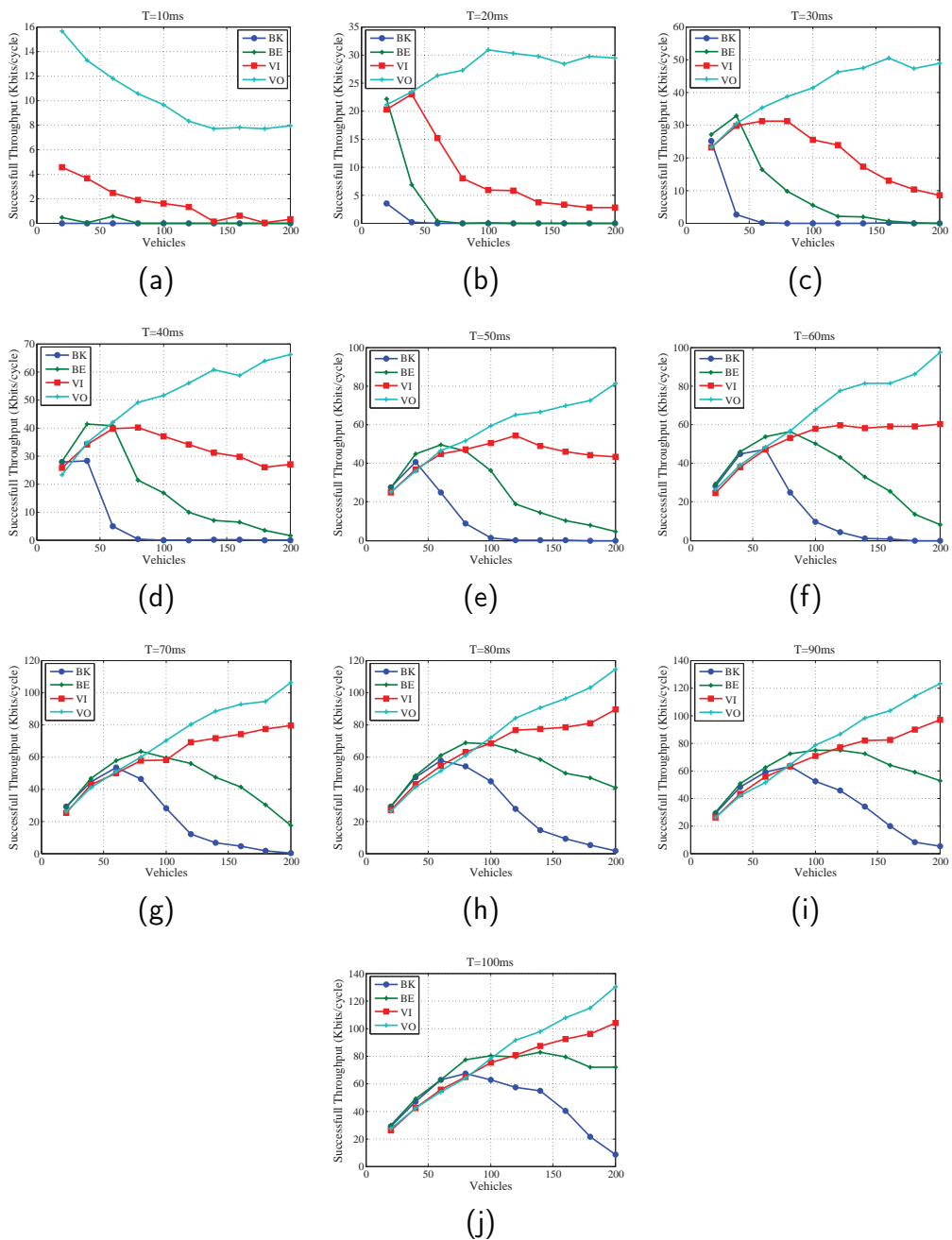


Fig. 5.11 Successful throughput

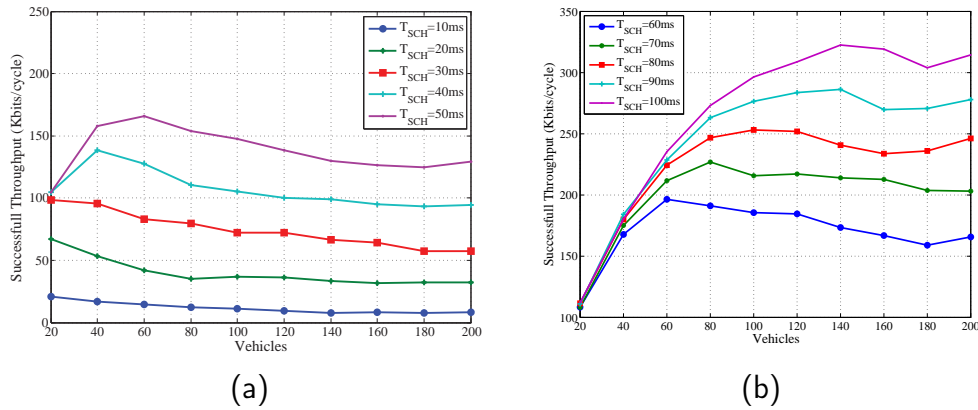


Fig. 5.12 Total successful throughput

Fig. 5.13 depicts the channel busy ratio for various SCH interval settings. It may be observed that the  $R_{busy}$  increases following the increase of contention vehicles. This is because the more vehicles there are, the more traffic there is. As a result, more channel duration will be occupied to transmit the increased traffic. Compared with the values of  $R_{busy}$  for different SCH intervals, it can be seen that the maximum channel busy ratio increases following the increase of the SCH interval when the SCH interval is less than 50ms. As discussed in Section 5.2.2.1, one of the reasons is because the 4ms guard interval is included in the SCH interval. During the guard interval, no messages are allowed to transmit. The guard interval takes a large portion of the SCH interval when the latter interval is short. As a result, the busy ratio for a short SCH interval is low. However, the guard interval cannot affect the busy ratio much when the SCH interval is greater than 50ms. The maximum busy ratios for different SCH interval settings are shown in Table 5.8. It can also be seen from Fig. 5.13 that the network is becoming saturated following the increase in contention vehicles. The saturated point presented by the number of contention vehicles denotes the saturated network capacity for different SCH interval settings; the results obtained in this study are shown in Table 5.9. The saturated network capacity is very important to the design of the infrastructure in VANETs.

Table 5.6 Service capacity under contention scenario

$T_{SCH}(ms)$	10	20	30	40	50	60	70	80	90	100
Users	3	10	15	21	25	30	35	39	44	50

Table 5.7 Network capacity for maximum successful throughput

$T_{SCH}(ms)$	10	20	30	40	50	60	70	80	90	100
Vehicles	20	20	20	40	60	60	80	100	140	140

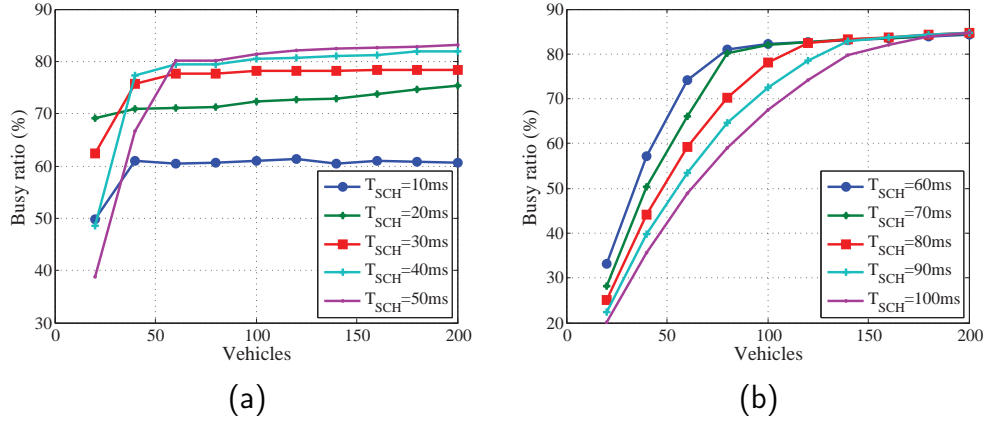


Fig. 5.13 Busy ratio

### 5.2.3 Discussion

In this section, the 802.11p MAC protocol is evaluated under both contention free and contention network conditions, with various SCH interval settings. The key QoS metrics, such as channel access probability, transmission reliability, throughput and successful throughput, latency and channel utilisation probability for different ACs with various SCH interval settings are evaluated. The evaluation, in contention free scenarios, is presented first; the maximum service capacity for each AC is obtained. The section then addresses the contention scenario, which is closer to the real-world environment. The performances of various SCH interval settings are compared and analysed. It may be concluded from this study that: (i) The VO and VI AC outperform BK and BE in a congested network environment; however, BK and BE could outperform VO and VI in terms of reliability and successful throughput under the scenario that the network traffic is low in volume. (ii) The key QoS metrics may be improved by increasing the SCH interval. (iii) The service capacity increases, following the increase of the SCH interval.

Based on these conclusions, the QoS and service capacity could be improved by adjusting the SCH interval. However, as discussed in Chapter 4, the safety related application transmitted in CCH is more critical. Hence, two instead of one service channels should be considered in some scenarios when the service traffic is heavy. The next

Table 5.8 Maximum busy ratio

$T_{SCH}(ms)$	10	20	30	40	50	60	70	80	90	100
$R_{busy}(\%)$	60.7	75.3	78.3	81.9	83.1	84.2	84.4	84.6	84.7	84.6

Table 5.9 Saturated network capacity

$T_{SCH}(ms)$	10	20	30	40	50	60	70	80	90	100
Vehicles	20	20	40	40	60	80	100	120	140	180

section, which takes two service channels into consideration, proposes and discusses a multi-SCH algorithm.

### 5.3 Multi-SCH Algorithm

As indicated above, a multi-SCH algorithm to consider two service channels in order to improve the network capacity and service ability in VANETs is proposed. The said algorithm is designed to function in conditions where the service traffic is heavy; therefore, conditions in which  $T_{SCH} < 50ms$  are not considered. In WAVE, each vehicle is expected to join a WBSS, which is a unique identifier for each communication zone. Vehicles must associate with only one WBSS at a time. Due to the high mobility of vehicles in VANETs, 802.11p simplifies the procedure to setup a WBSS without active scanning, association, and authentication procedures. To establish a WBSS, as shown in Fig. 5.14, a provider periodically broadcasts the WSA [13] on the CCH. WSA contains the necessary information for the users to join the WBSS, such as the WBSS identifier, the availability of a service, the selected SCH, synchronisation timing information etc. In the meantime, all the vehicles have to listen to the CCH during the CCH intervals. Thereafter, a user learns about available WBSSs and joins the WBSS, which provides the services in which the user is interested by simply switching to the advertised SCH during SCH intervals. By utilising a single PHY device, only one selected SCH is advertised in WSA. By employing a multi-PHY device, more SCHs can work simultaneously. The multi-SCH algorithm proposed in this section is designed to optimise the cooperation between SCHs in order to balance the traffic load and improve the QoS.

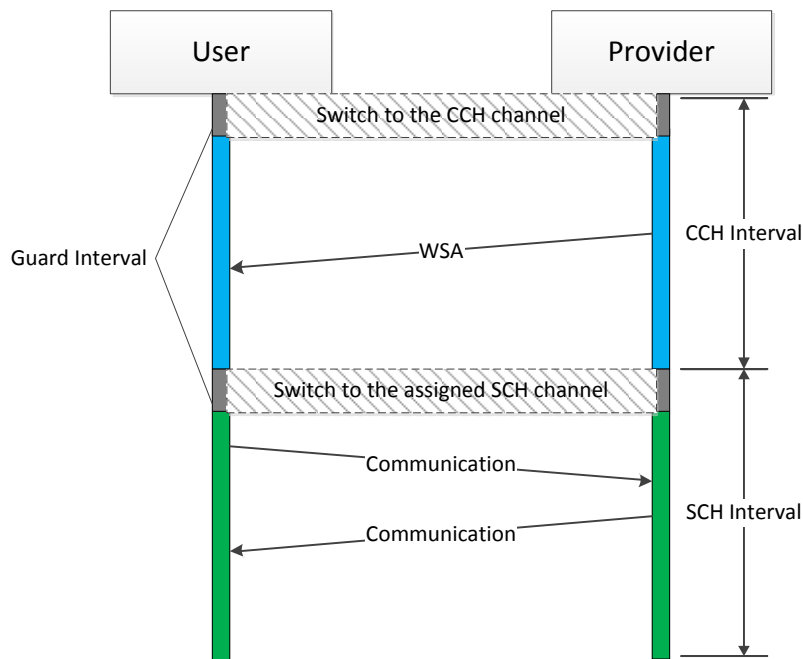


Fig. 5.14 Service access

### 5.3.1 Proposed Algorithm

The basic idea of the proposed multi-SCH algorithm is to consider two SCHs when the network traffic is heavy. The two SCHs need to be working cooperatively in order to balance the traffic load and achieve a better QoS. The network traffic could alter for different time periods, since the vehicle density varies according to the time of day. Hence, in the proposed algorithm, the second SCH will be activated only when the network traffic is above a certain threshold. The WSA message contains all the available SCHs' information. The service provider periodically broadcasts the WSA on the CCH every 100ms. When the two SCHs are both activated, the network traffic will be assigned to these two SCHs according to the real-time traffic. The proposed algorithm contains four steps shown as follows:

1. **Traffic Monitoring:** RSU monitors each SCH's traffic load, which is presented as the channel busy ratio;
2. **SCH Activation:** If there is only one activated SCH and the current traffic load is above a threshold, the second SCH will be activated;
3. **Traffic Balance:** Once there are two SCHs working simultaneously, the SCH with a lighter traffic load will obtain a higher priority to be accessed. The SCH priority information will be distributed to vehicles via WSA. Once a vehicle receives the WSA, it selects the SCH that has the lighter traffic load from the WSA message and switches into the selected SCH during a SCH interval;
4. **SCH Deactivation:** The second SCH will be deactivated when the traffic load is less than a certain threshold where the threshold is also presented as the channel busy ratio.

#### 5.3.1.1 Traffic Monitoring

During SCH interval, the RSU will record the channel busy time for each SCH. The channel busy ratio  $R_{busy}$  for each SCH will be calculated once the channel switches to CCH. The details of the traffic monitoring algorithm are specified in Algorithm 4.

#### 5.3.1.2 SCH Activation

In the proposed multi-SCH algorithm, the second SCH will be activated if the current traffic load is above a certain threshold. Hence, the key for SCH activation is to decide the channel activation threshold  $\Gamma_{up}$ . In this study, the main purpose of the proposed algorithm is to improve the service ability and QoS; hence, the point of maximum successful throughput is set as the channel activation threshold  $\Gamma_{up}$ . In a real-world network environment, the real-time maximum successful throughput cannot be obtained.



---

### Algorithm 4 Traffic monitoring algorithm

---

```

1: switch to SCH interval
2:  $T_{busy} \leftarrow 0$ 
3: while SCH interval do
4:   if the channel is busy then
5:     record the busy duration  $T_{duration}$ 
6:      $T_{busy} = T_{busy} + T_{duration}$ 
7:   end if
8: end while
9:  $R_{busy} = \frac{T_{busy}}{T_{SCH}}$ 

```

---

However, the relation between the successful throughput and channel busy ratio can be obtained from the simulation results obtained in Section 5.2.2.2. The results are represented in Fig. 5.15. The busy ratios for maximum successful throughput obtained from Fig. 5.15, are depicted in Table 5.10, where the scenarios that  $T_{SCH} < 50ms$  are not included. The busy ratios for maximum successful throughput are taken as the channel activation threshold  $\Gamma_{up}$ . It can be observed that the  $\Gamma_{up}$  approximates 0.8 for various SCH interval settings. As a result, the value of the channel activation threshold is set as 0.8 in this study. The details of the SCH activation algorithm are specified in Algorithm 5.

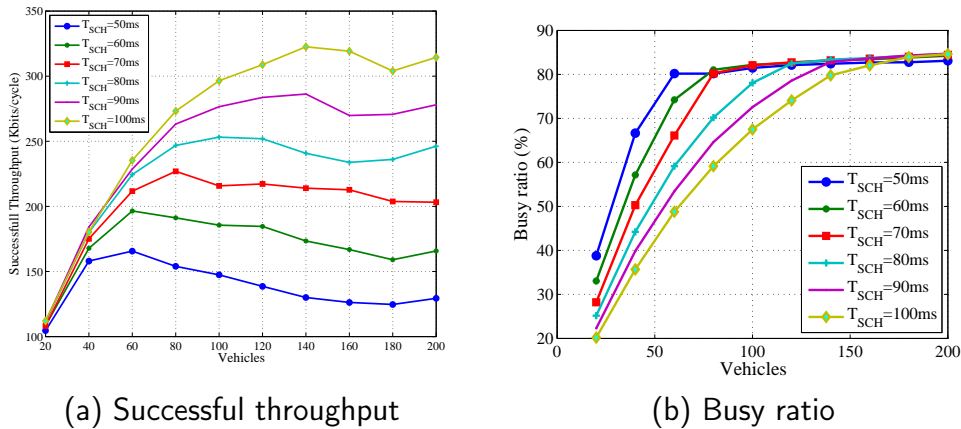


Fig. 5.15 Relation between successful throughput and channel busy ratio

Table 5.10 Channel activation threshold

$T_{SCH}(ms)$	50	60	70	80	90	100
Busy ratio (%)	80	75	80	79	82	80
Vehicles	60	60	80	100	140	140

**Algorithm 5** SCH activation algorithm

---

```

1: switch to CCH interval
2: if only one SCH channel is activated then
3:    $R_{busy1} \leftarrow$  the busy ratio of SCH1
4:   if  $R_{busy1} \geq \Gamma_{up}$  then
5:     activate SCH2
6:   end if
7: end if

```

---

**5.3.1.3 Traffic Balance**

The number of cars that move in/out of the RSU coverage in a 100ms cycle needs to be discussed before the traffic balance approach is presented. Suppose the speed of a vehicle is  $v = 120Km/h$ ; the length that a vehicle can move during a 100ms can be determined as  $L = v \times 100ms = 3.33m$ . On a highway, the distance between two cars is normally longer than 50m; here, suppose it is 50m. The car density for one lane is then determined as  $\rho = 1/50 = 0.02car/m$ . Hence, for a six-lane bio-direction highway, the average number of vehicles that can move in/out a RSU communication range in a 100ms cycle can be determined as  $N_{IO} = 6 \times \rho \times L = 0.36car$ . As a result, on average, there will be less than one car that is able to move into/out of a RSU coverage during one cycle.

The idea of the traffic balance approach is to broadcast the available SCHs' information through the WSA message. For each cycle, the RSU will broadcast the WSA on CCH; the number of SCH is adapted according to the real-time value of  $R_{busy}$ . There will be only one activated SCH if the  $R_{busy}$  is less than the channel activation threshold  $\Gamma_{up}$ . On the other hand, the second SCH will be activated if the  $R_{busy}$  is greater than the threshold  $\Gamma_{up}$ . In order to not affect the ongoing transmission, only the new vehicles that have just moved into the coverage of this RSU will be assigned to the new activated SCH. The WSA contains two SCHs' information in 'Service Info' as illustrated in Fig. 5.16, where the PSIDs are the same, to indicate that they belong to the same RSU. As stated in [13], the Channel Index provides a pointer to the nth set of channel parameters within Channel Info in the WSA and indicates the service channel where the advertised service is being offered. Channel Index of 1 indicates the first set of parameters, Channel Index of 2 indicates the second set of parameters, and so on. For the newly oncoming vehicles, they will choose the first Channel Index if they are interested in the service. However, for the existing vehicles in this RSU, they will stay on the same SCH if the SCH is still available and listed in the WSA. The order of these two SCH channels is determined according to the real-time value of  $R_{busy}$ . The channel with a low busy ratio will obtain the first place in WSA. As a result, the newly oncoming vehicle will join the channel which has the lighter traffic load and thereby balance the traffic between two SCHs. The details of the WSA generation and SCH selection algorithm are specified in

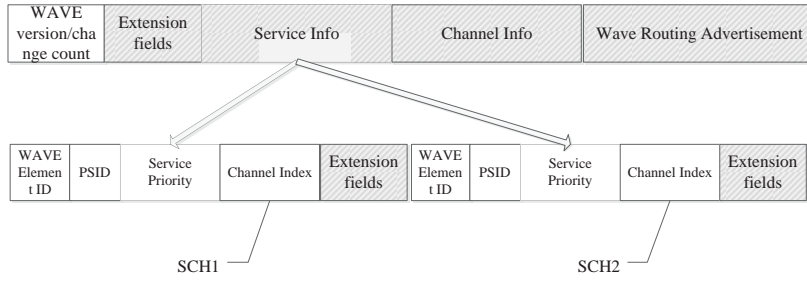


Fig. 5.16 WSA format

---

### Algorithm 6 WSA algorithm

---

- 1: switch to CCH interval
  - 2: **if** one activated SCH **then**
  - 3:   set one SCH in WSA
  - 4: **else**
  - 5:    $R_{busy1} \leftarrow$  the busy ratio of SCH1
  - 6:    $R_{busy2} \leftarrow$  the busy ratio of SCH2
  - 7:   **if**  $R_{busy1} > R_{busy2}$  **then**
  - 8:     set SCHs in WSA in order of SCH2 SCH1
  - 9:   **else**
  - 10:   set SCHs in WSA in order of SCH1 SCH2
  - 11:   **end if**
  - 12: **end if**
  - 13: Broadcast WSA message
- 

---

### Algorithm 7 SCH selection algorithm

---

- 1: received a WSA message
  - 2: check the PSID
  - 3: **if** the PSID is new **then**
  - 4:    $SCHID \leftarrow$  the first SCH index
  - 5: **else**
  - 6:   **if**  $SCHID =$  the first SCH index **||**  $SCHID =$  the second SCH index **then**
  - 7:     break
  - 8:   **else**
  - 9:      $SCHID =$  the first SCH index
  - 10:   **end if**
  - 11: **end if**
  - 12: switch to SCHID during SCH interval
- 

Algorithms 6 and 7 respectively.

#### 5.3.1.4 SCH Deactivation

The idea of SCH deactivation is to shut down one SCH if the traffic load is less than a threshold in order to save energy and prolong the lifetime of the PHY device. Suppose  $\Gamma_{down}$  denotes the channel deactivation threshold;  $\Gamma_{down}$  is determined as  $\Gamma_{down} =$

Table 5.11 Channel deactivation threshold

$T_{SCH}(ms)$	50	60	70	80	90	100
Busy ratio (%)	40	40	40	40	40	40
Vehicles	20	25	30	35	40	50

$\alpha \times \Gamma_{up}$ , where  $\alpha$  is a coefficient. In this study,  $\alpha$  is set as 0.5 based on the simulation results in Fig. 5.15. The corresponding users for the setting of  $\Gamma_{down} = 0.5 \times \Gamma_{up}$  are depicted in Table 5.11. As depicted in Fig. 5.17, compared with the channel activation threshold represented in Table 5.10, it is clear that the total number of users for channel deactivation threshold is less than the number of users for the channel activation threshold. Hence, the setting of  $\Gamma_{down}$  should ensure that one SCH is able to handle the current users. All the current users will be reassigned to one SCH if  $R_{busy} < \Gamma_{down}$  for both SCHs. The details of the SCH deactivation approach are specified in Algorithm 8.

In general, the proposed multi-SCH algorithm contains two portions: the RSU algorithm and the OBU algorithm. The RSU algorithm contains traffic monitoring, SCH activation, traffic balance and SCH deactivation processes. The full version of the RSU algorithm, which is depicted in Algorithm 9, can be derived from Algorithm 4, Algorithm 5, Algorithm 6 and Algorithm 8. The OBU algorithm, which focuses on the SCH selection, based on the available SCHs' information from the WSA, contains only the SCH selection algorithm, as specified in Algorithm 7.

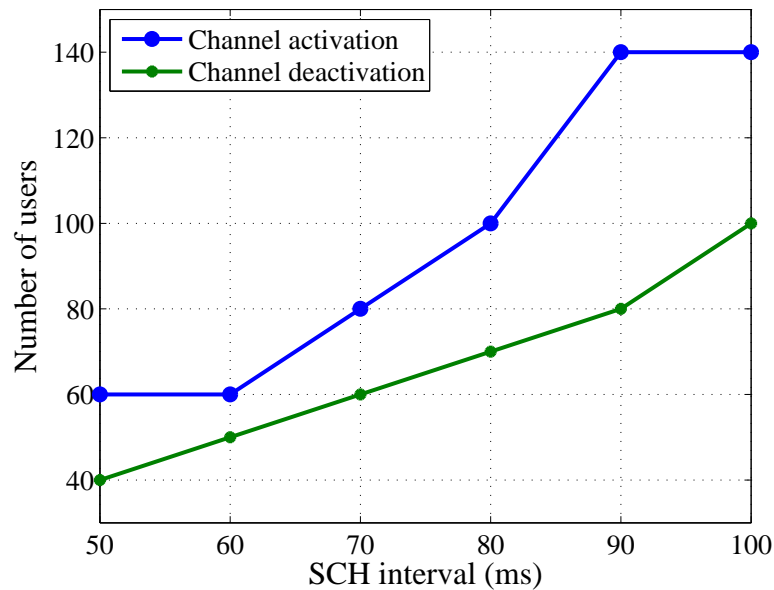


Fig. 5.17 Comparison of users

---

**Algorithm 8** SCH deactivation algorithm

---

```
1:  $\Gamma_{up} \leftarrow 0.8$ 
2:  $\Gamma_{down} \leftarrow 0.5 \times \Gamma_{up}$ 
3: switch to CCH interval
4: if two activated SCHs then
5:    $R_{busy1} \leftarrow$  the busy ratio of SCH1
6:    $R_{busy2} \leftarrow$  the busy ratio of SCH2
7:   if  $R_{busy1} < \Gamma_{down}$  and  $R_{busy2} < \Gamma_{down}$  then
8:     set SCH1 in WSA
9:     shut SCH2 down
10:  end if
11: end if
12: Broadcast WSA message
```

---

### 5.3.2 Validation and Discussions

The proposed multi-SCH algorithm is also evaluated based on the Veins 2.0 simulation platform. In the simulations conducted, the simulation configurations defined in Section 5.2.1 are adopted with some modifications. The traffic flow depicted in Table 5.3 and simulation settings in Table 5.4 are also used. The multi-SCH algorithm will handle two SCHs according to the real-time network traffic. The real-time channel-busy ratio is the key parameter of the proposed algorithm. The various SCH intervals only affect the SCH activation and deactivation threshold obtained in Tables 5.10 and 5.11. As a result, it is not necessary to evaluate the proposed multi-SCH algorithm with various SCH intervals. In the conducted simulations, the SCH interval is set as 50ms for all scenarios. In order to analyse the entire process of the multi-SCH algorithm, three simulation scenarios are considered in this section and are depicted as follows:

1. **SCH Activation:** In this scenario, the number of vehicles in a RSU communication range remains at 60. As listed in Table 5.10, the 60 vehicles is merely the SCH activation threshold. In order to evaluate the QoS for the scenario under which the second SCH is activated and the traffic of the two SCHs is becoming balanced, suppose there is only one vehicle in and one vehicle out of a RSU coverage during one 100ms cycle.
2. **Traffic Balance:** In this scenario, the number of vehicles in a RSU communication range keeps increasing from 60 to 120. Two SCHs are both working and the performance of the traffic balance algorithm will be evaluated and focused on.
3. **SCH Deactivation:** In this scenario, the number of vehicles in the RSU range decreases from 60 to 1 in order to simulate the SCH deactivation function.

### 5.3.2.1 SCH Activation

In the SCH activation process, the second SCH will be activated once the channel busy ratio is greater than the channel activation threshold. The simulation results of the channel busy ratio during the SCH activation process are shown in Fig. 5.18. It may be seen that the busy ratio for the single SCH is slightly larger than the channel activation threshold  $\Gamma_{up}$ . Hence, the second SCH is activated. As discussed in Section 5.3.1.3, only the newly oncoming vehicles will be assigned to the new SCH. Hence, as depicted in Fig. 5.18, the channel busy ratios of the two SCHs are becoming balanced after 30 cycles, since it was supposed, in the former section, that only one vehicle was moving in and out of the RSU during one cycle.

The simulation results of throughput during the SCH activation process are illustrat-

---

#### Algorithm 9 RSU algorithm

---

```

1:  $\Gamma_{up} \leftarrow 0.8$ 
2:  $\Gamma_{down} \leftarrow 0.5 \times \Gamma_{up}$ 
3: switch to SCH interval
4:  $T_{busy} \leftarrow 0$ 
5: while SCH interval do
6:   if the channel is busy then
7:     record the busy duration  $T_{duration}$ 
8:      $T_{busy} = T_{busy} + T_{duration}$ 
9:   end if
10: end while
11:  $R_{busy} = \frac{T_{busy}}{T_{SCH}}$ 
12: switch to CCH interval
13: if one activated SCH then
14:   set one SCH in WSA
15:    $R_{busy1} \leftarrow$  the busy ratio of SCH1
16:   if  $R_{busy1} \geq \Gamma_{up}$  then
17:     activate SCH2
18:   end if
19: else
20:    $R_{busy1} \leftarrow$  the busy ratio of SCH1
21:    $R_{busy2} \leftarrow$  the busy ratio of SCH2
22:   if  $R_{busy1} < \Gamma_{down}$  and  $R_{busy2} < \Gamma_{down}$  then
23:     set SCH1 in WSA
24:     shut SCH2 down
25:   else if  $R_{busy1} > R_{busy2}$  then
26:     set SCHs in WSA in order of SCH2 SCH1
27:   else
28:     set SCHs in WSA in order of SCH1 SCH2
29:   end if
30: end if
31: Broadcast WSA message

```

---

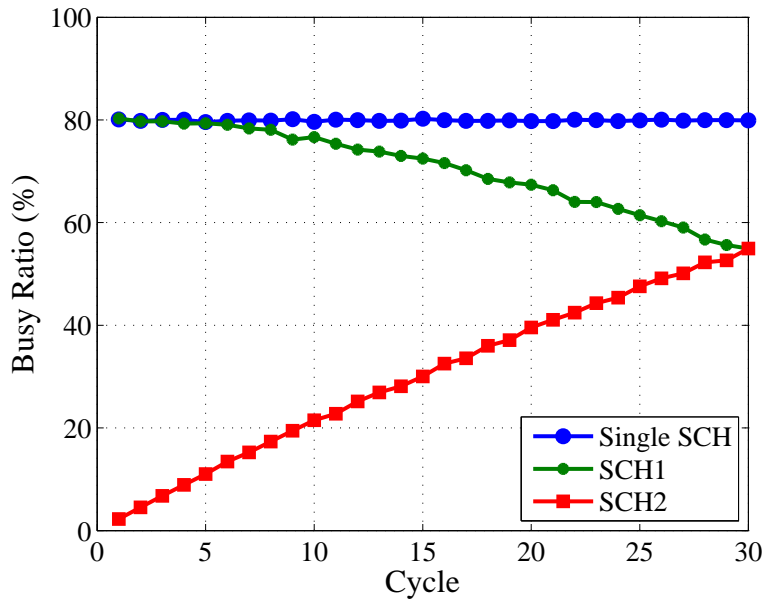


Fig. 5.18 Comparison of busy ratio\_SCH activation

ed in Fig. 5.19. It may be observed that the traffic load of the two SCHs are becoming balanced after 30 cycles, since only the newly oncoming vehicles are assigned to the SCH2. Compared with the single SCH algorithm, the multi-SCH algorithm does not improve the throughput during the SCH activation process. However, as shown in Fig. 5.20, the successful throughput can be greatly improved via multi-SCH algorithm. The successful throughput is determined by the received messages; more traffic causes more collisions and fewer received messages. The multi-SCH algorithm reduces the traffic of

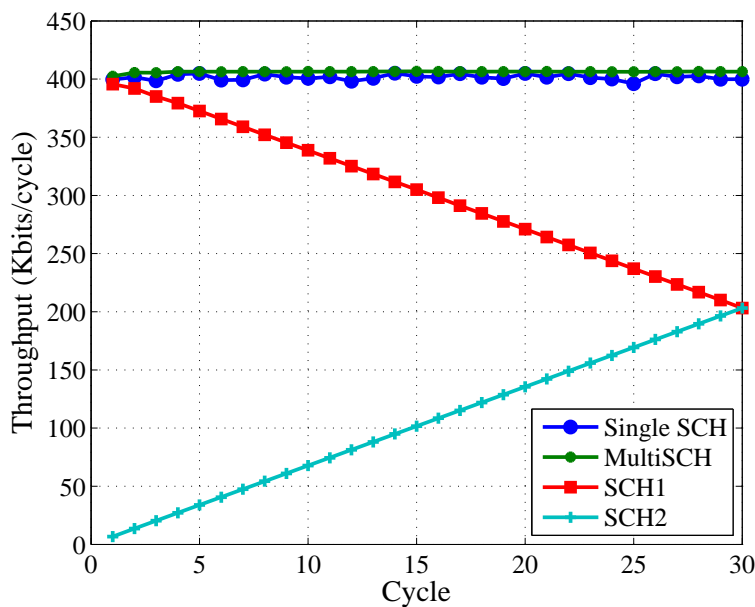


Fig. 5.19 Comparison of throughput\_SCH activation

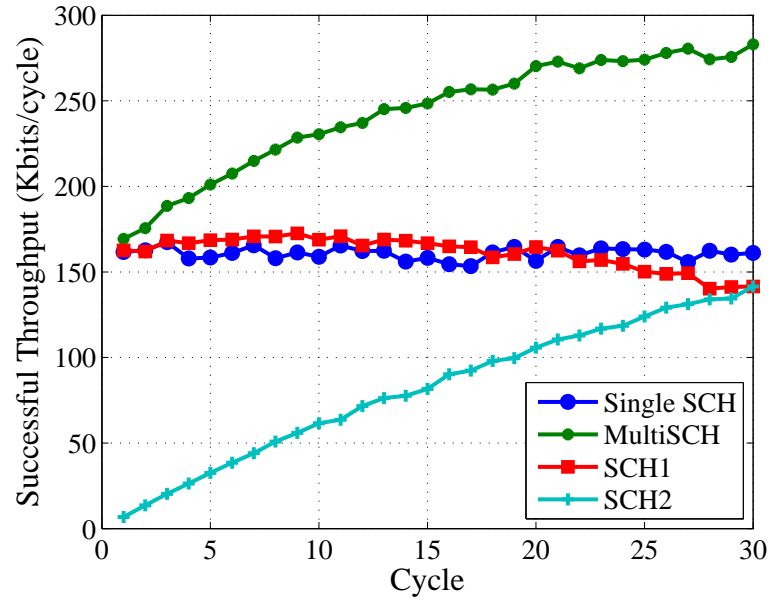


Fig. 5.20 Comparison of successful throughput\_SCH activation

SCH by adopting two SCHs instead of one when the SCH channel busy ratio is detected as greater than the threshold  $\Gamma_{up}$ . The reduced traffic decreases the contention and collision; as a result, more messages are successfully received. It can be noticed that the successful throughput of two SCHs is becoming similar after 30 cycles. Compared to the single SCH algorithm, the successful throughput is improved by up to 76% by the multi-SCH algorithm during the SCH activation process.

### 5.3.2.2 Traffic Balance

In the traffic balance process, the traffic load of the two SCHs will be kept in balance via the channel-busy ratio monitoring and traffic balance algorithm. In this simulation scenario, the number of vehicles in a RSU communication range increases continuously from 60 to 120. The simulation results of the channel-busy ratio are shown in Fig. 5.21. It may be observed that the channel busy ratios for these two SCHs are very close to each other, no matter how many vehicles are in the network. The channel-busy ratio for multi-SCH increases according to the increase in the number of vehicles. In the meantime, the channel busy ratio for the single SCH algorithm does not change greatly since it is already saturated.

The simulation results of throughput during the traffic balance process are shown in Fig. 5.22. It may be observed that the throughputs for these two SCHs are very balanced, with the throughput increase following the increase in vehicle numbers. Furthermore, it can be seen that the total throughput of the multi-SCH algorithm is greater than the throughput of the single SCH algorithm, indicating that the multi-SCH algorithm can improve the throughput. As demonstrated in Fig. 5.10, the throughput diminishes due



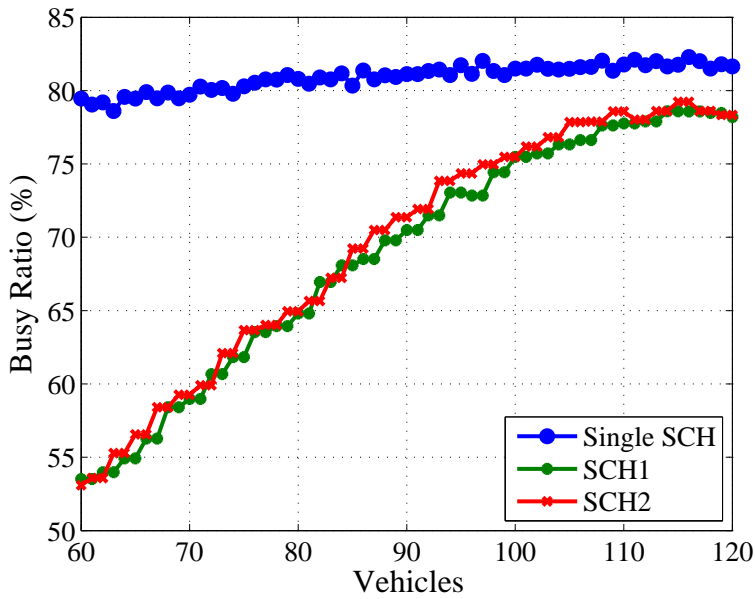


Fig. 5.21 Comparison of channel-busy ratio\_traffic balance

to the decrease of the corresponding sent ratio. The sent ratio decreases following the increase of contention vehicles. During the SCH activation process, there were only 60 contention vehicles and the advantage of the multi-SCH algorithm in terms of throughput is not explored. However, following the increase in number of contention vehicles, the multi-SCH algorithm outperforms the single SCH algorithm since the contention vehicles are reduced via distribution to two SCHs. By comparison to the single SCH algorithm, the throughput can be improved up to 33% by the multi-SCH algorithm in this simulation scenario.

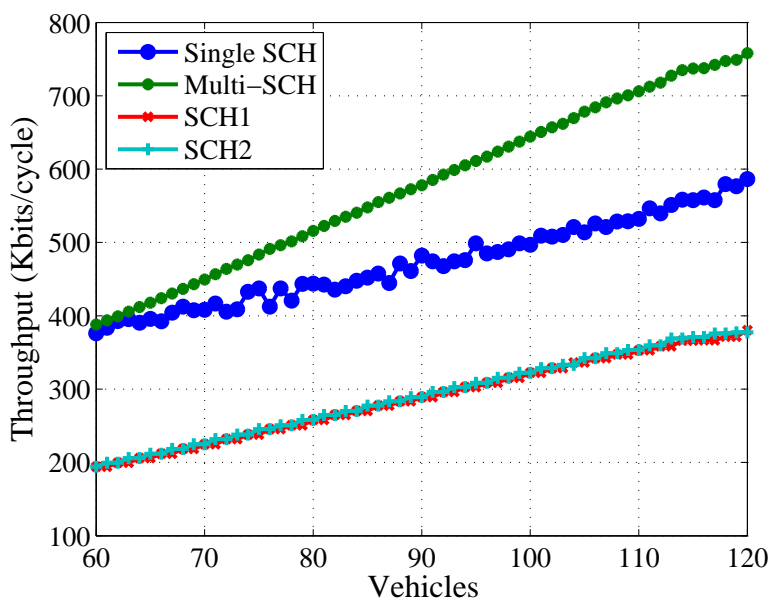


Fig. 5.22 Comparison of throughput\_traffic balance

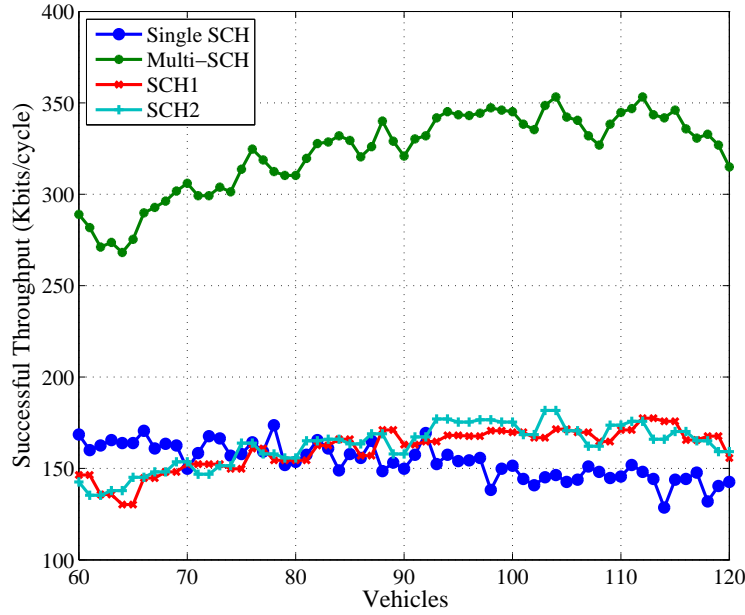


Fig. 5.23 Comparison of successful throughput\_traffic balance

Fig. 5.23 displays the simulation results of successful throughput during the traffic balance process. It can be observed that the successful throughput with the single SCH decreases, following an increase in the number of vehicles, because the increased vehicle numbers caused more contention and, as a result, a worse performance in terms of successful throughput. The successful throughputs for SCH1 and SCH2 are also very similar. The successful throughput increased minimally, following the increase of vehicle numbers and decrease of the throughput when the network is saturated. This phenomenon is similar to the result depicted in Fig. 5.12. In comparison to the single SCH algorithm, the multi-SCH algorithm is able to improve the successful throughput by up to 165%.

### 5.3.2.3 SCH Deactivation

In the SCH deactivation process, SCH2 will be deactivated if the traffic load is decreasing and the channel busy ratio is less than the threshold  $\Gamma_{down}$ . The simulation results of this channel-busy ratio during the channel deactivation process are indicated in Fig. 5.24. In this simulation scenario, the number of vehicles decreases from 60 to 1. It can be noticed that the SCH2 is deactivated when the channel-busy ratio is less than the channel deactivation threshold  $\Gamma_{down} = 0.4$ . SCH1 will take over all the services once the SCH2 is deactivated. As a result, the busy ratio of SCH1 suddenly increases at the threshold point.

The simulation results of throughput and successful throughput during channel deactivation processes are shown in Fig. 5.25 and Fig. 5.26 respectively. It can be observed

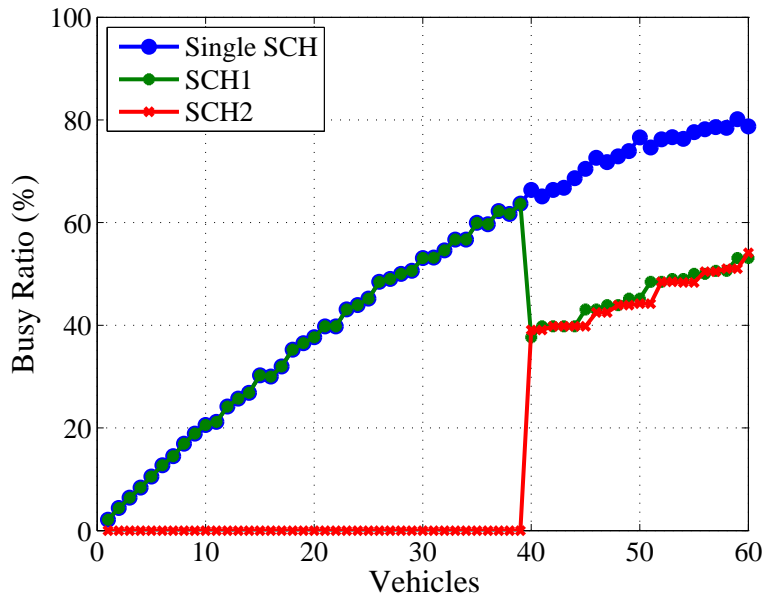


Fig. 5.24 Comparison of channel-busy ratio\_SCH deactivation

that the throughput and successful throughput keeps balance before the deactivation of SCH2. The multi-SCH works exactly like the single SCH algorithm once the SCH2 is deactivated.

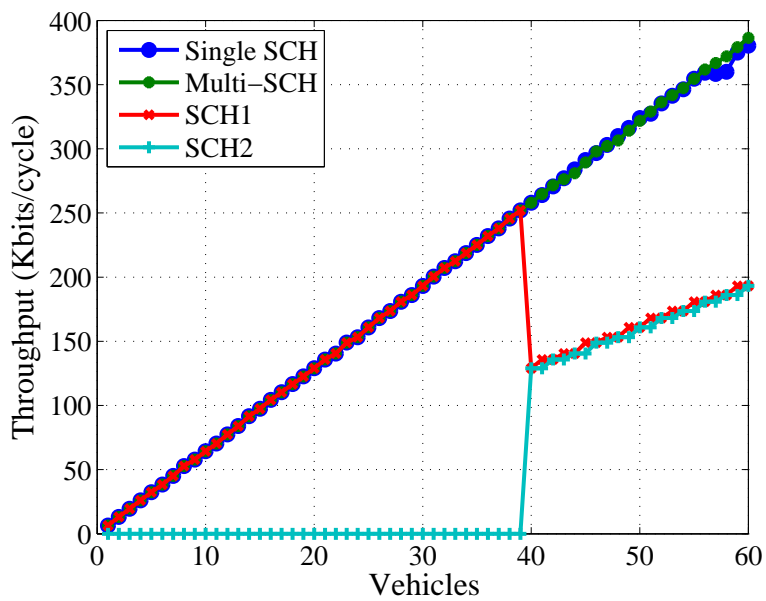


Fig. 5.25 Comparison of throughput\_SCH deactivation

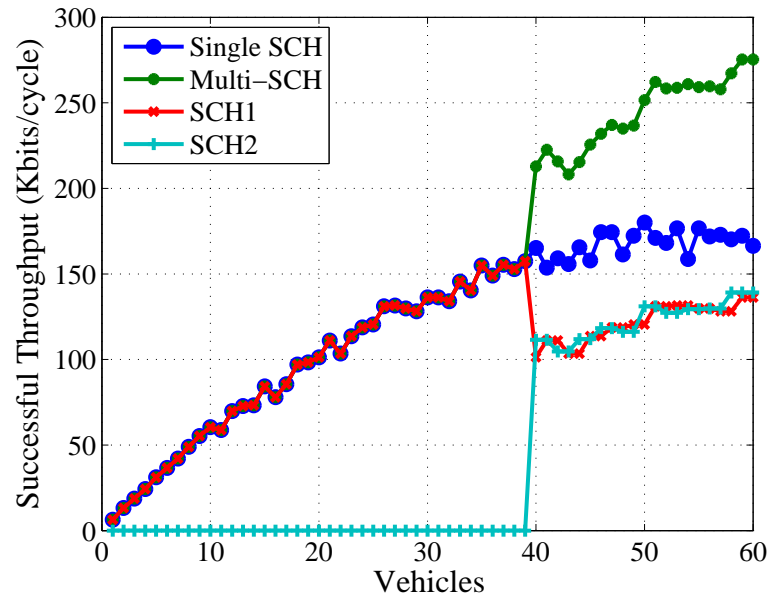


Fig. 5.26 Comparison of successful throughput\_SCH deactivation

## 5.4 Conclusion

In this chapter, the evaluation and enhancement of 802.11p on SCH are presented and discussed. Firstly, the 802.11p MAC protocol is evaluated. The key QoS metrics such as channel access probability, transmission reliability, throughput and successful throughput, latency and channel utilisation probability for different ACs with various SCH interval settings are evaluated. Based on the evaluation results, a multi-SCH algorithm is proposed and validated. The proposed multi-SCH algorithm aims to improve the QoS of 802.11p in-service channel, considering two SCH channels instead of one. The proposed algorithm contains three steps to manage the two SCHs to work cooperatively in both light and heavy traffic environments. The proposed multi-SCH algorithm is validated based on the Veins simulation platform. The simulation results indicate that the multi-SCH algorithm may improve the performance of 802.11p in terms of throughput and successful throughput. As a result, the service ability of 802.11p can be improved by the proposed multi-SCH algorithm.



# Chapter 6

## Conclusions and Recommendations

### 6.1 Introduction

This chapter summarises all the research relevant to this topic that has been carried out to date as well as the conclusions drawn from the results obtained. The benefits of this study and recommendations for future research are also briefly discussed.

### 6.2 Statement of Initial Objective

VANETs have attracted much attention owing to our society's transportation problems such as traffic congestion, traffic accidents, lack of mobility and accessibility and so forth. VANETs have certain characteristics due to the high speed mobility of vehicles, such as rapid changes of topology, potentially large-scale, veritable network density and so on. The 802.11p standard has increasingly attracted attention as an important aspect of the WAVE protocol in VANETs. Because the 802.11p standard is still a new and draft standard, the important metrics of its QoS, such as collision, reliability, throughput and delays still needs to be analysed and improved in order to meet the requirements of the realistic vehicular communication networks. Hence, the objective of this study was to evaluate and improve the performance of the 802.11p protocol to offer a more reliable and efficient service in VANETs.

### 6.3 Achievements of the Project

In this study, the IEEE 802.11pMAC protocol was evaluated and improved for both CCH and SCH applications. Firstly, the study focussed on the CCH and the performance of 802.11p on CCH, which was evaluated based on INET and Veins' frameworks with various CCH intervals. The important metrics of QoS, such as collision, reliability, throughput, delays and network capacity were evaluated and discussed. The results indicate that

the performance of the IEEE 802.11p MAC protocol could be improved by means of extending the CCH interval. A CCH adaptive algorithm for the IEEE 802.11pMAC protocol was then proposed, in which the CCH interval was adjusted according to the average number of contention vehicles in a VANET. It was demonstrated that the CCH adaptive algorithm is able to improve the channel utilisation ratio (up to 60%) for a low traffic scenario and increase the reliability for a heavy traffic scenario by adjusting the CCH interval. Secondly, the evaluation and enhancement of 802.11p on SCH were presented and discussed. The performances of SCH with various SCH intervals were evaluated based on the Veins simulation platform. The key QoS metrics such as channel access probability, transmission reliability, throughput and successful throughput, latency and channel utilisation probability for different ACs with various SCH interval settings were evaluated. Based on the evaluation results, a multi-SCH algorithm was proposed and validated. The proposed multi-SCH algorithm aims to improve the QoS of 802.11p in service channel, considering two SCH channels instead of one. The proposed algorithm contains three steps to manage the two SCHs to function cooperatively for both light and heavy traffic environments. The proposed multi-SCH algorithm was found to be able to improve the performance of 802.11p in terms of throughput, successful throughput as well as the service ability.

## 6.4 Benefits of the Study

The benefits of this study include:

1. The evaluation of 802.11p CCH covers the important QoS metrics; therefore, the evaluation results can help to analyse the performance of 802.11p under various traffic density conditions. The network capacity obtained in this study is also helpful to the designing of VANETs.
2. The proposed CCH adaptive algorithm can improve the QoS of VANET for the situation where the OBU is equipped with only one transceiver. The critical safety applications are guaranteed and the channel utilisation is improved.
3. The evaluation of 802.11p SCH can assist in analysing the network capacity and service ability. The evaluation results are significant for the designing of RSU coverage in VANETs.
4. Due to the characteristics of VANETs, the requirements of high throughput and low latency are critical in VANETs. The proposed multi-SCH algorithm is able to improve the QoS of 802.11p in-service channel, when considering two SCH channels, instead of one,. The service capacity and service ability may be improved by the proposed multi-SCH algorithm.

### 6.5 Recommendations for Future Study

Some of the future studies in this area could include the following:

1. Proposing an analytical model to evaluate the performance of the IEEE 802.11p MAC protocol with various CCH/SCH interval settings;
2. Optimising the SCH activation and deactivation based on the provided service traffic;
3. Improving the proposed multi-channel MAC protocol to improve the SCH service ability when considering more than two SCHs;
4. Developing a SCH interval adjusting algorithm based on the real-time network load.

### 6.6 Final Conclusion

This project focused on the scheduling and QoS of IEEE802.11p MAC protocol. Both of the safety and service applications working on CCH and SCH respectively are covered. A comprehensive evaluation of the 802.11p MAC protocol was obtained based on the latest simulation platforms. The evaluation results are significant for the analyst as well as for the design and development of the MAC protocol in VANETs. Two enhancement algorithms are proposed for the 802.11p MAC protocol: the CCH adaptive algorithm for safety applications and the multi-SCH algorithm for service applications. Both of these algorithms are designed and validated for improving the QoS of IEEE802.11p MAC protocol in VANETs. The simulation results demonstrate that the important QoS metrics such as the reliability, throughput, successful throughput, network capacity and channel utilisation are improved by the proposed algorithms in this project.





# Appendix A

## Simulation Node Code\_Veins

```
import org.mixim.modules.mobility.LinearMobility;
import org.mixim.modules.application.ieee80211p.TestWaveApplLayer;
import org.mixim.base.modules.BaseArp;
import org.mixim.modules.nic.Nic80211p;

    module mls11pNode
    {
    parameters:
    @display("p=10,10;b=4,4,rect;o=white");

        gates:
    input radioIn; // gate for sendDirect

        submodules:
    appl: TestWaveApplLayer
    @display("p=90,50;b=100,20,rect");

        arp: BaseArp
    @display("p=257,28;b=30,25");

        nic: Nic80211p
    @display("p=90,150;b=100,20,rect");

        mobility: LinearMobility
    @display("p=130,172;i=block/cogwheel");
```

connections:

```
nic.upperLayerOut -> appl.lowerLayerIn;  
nic.upperLayerIn <- appl.lowerLayerOut;  
nic.upperControlOut -> appl.lowerControlIn;  
nic.upperControlIn <- appl.lowerControlOut;
```

```
    radioIn -> nic.radioIn;  
}
```

# Appendix B

## Publication

- 1 Miao, L., Djouani, K., Kurien, A. and Noel, G., A competing algorithm for gradient based routing in wireless sensor networks, in WINSYS 2010, 26th-28th July 2010, Athens, Greece.
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- 4 Miao, L., Djouani, K., Kurien, A. and Noel, G., Network coding and competitive approach for gradient based routing in wireless sensor networks, Ad Hoc Networks, 2012, doi: 10.1016/j.adhoc.2012.01.001 (ISI Master Index Journal, Impact Factor: 1.592).
- 5 Miao, L., Djouani, K., Van Wyk, B. J. and Hamam, Y., Evaluation and enhancement of IEEE 802.11p Standard: A Survey, Mobile Computing (MC), Vol.1 Iss.1.
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# Appendix C

## Certification

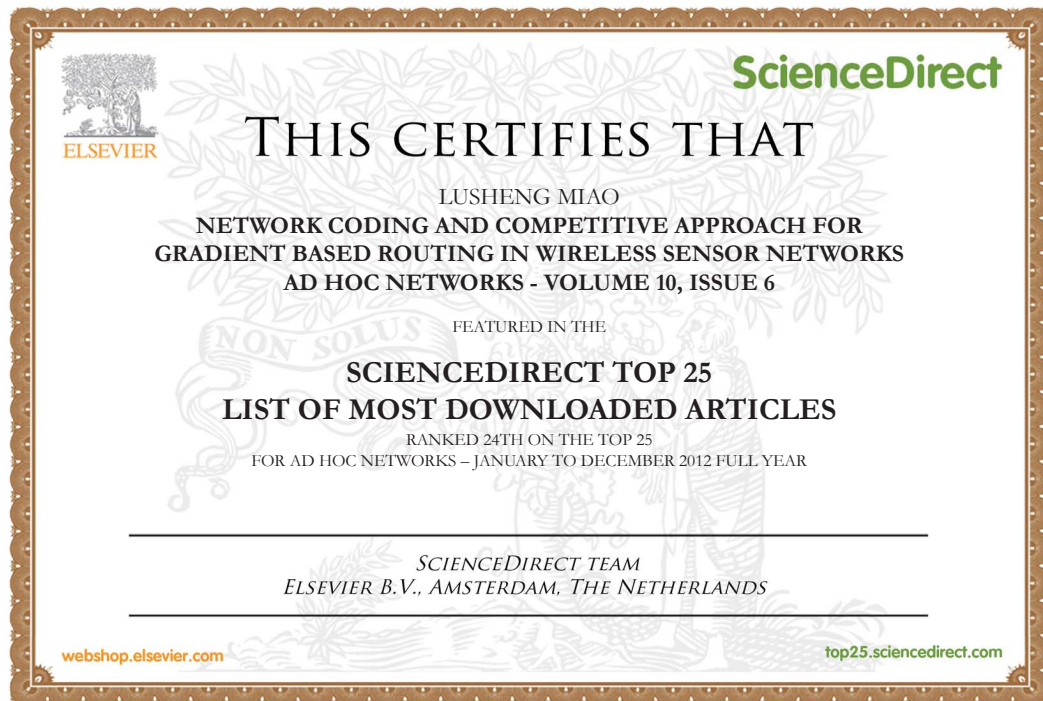


Fig. C.1 Certification



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