Solving the Performance Puzzle of DSRC Multi-Channel Operations

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Dedication

This thesis is dedicated to my parents, my sister, my love and the whole research community here at McGill University

Abstract

The IEEE 802.11p based Dedicated Short Range Communication (DSRC) protocol is a key enabling technology for enhancing road safety and transportation efficiency, and is being seriously considered by major research centres and automobile manufacturers. Wireless Access in Vehicular Environments (WAVE) 1609.4 is a new amendment that enables multi-channel operations in DSRC. Operating intervals are divided into alternating Control Channel (CCH) Intervals and Service Channel (SCH) Intervals, which halve the duration of channel intervals and operating interval. This alternating feature causes high packet losses in CCH and low throughput in SCH, hence hinders the deployment of this protocol. The key goal of our work is to provision sufficient reliability for real-time safety messages in CCH while optimising non-safety service delivery in SCH. We have developed analytical models for both broadcasting and unicasting to explore the relationship among traffic density, CCH packet loss ratio, SCH throughput, and the duration of each kind of intervals. Unlike assigning fixed channel interval in error-prone default channel access approach, we develop a multi-channel coordination algorithm which adaptively adjusts the duration of intervals to achieve better performance and reliability based on these models. Theoretical analysis and extensive simulation results demonstrate the accuracy of our model and the efficacy of the proposed algorithm. The algorithm almost doubles SCH throughput in low traffic density scenario and reduces packet loss ratio by up to 30%. We also show that the proposed algorithm converges rapidly to the optimal channel interval division.

ABRÉGÉ

Le protocole IEEE 802.11p dédié *à* la communication sur des distances courtes (DSR-C) est présentement considéré par les centres de recherches et les centres manufacturiers d'automobiles comme un protocole améliorant la sécurité routi*à*re ainsi que l'efficacité du transport routier. Le protocole WAVE 1609.4 constitue un nouvel amendement envers D-SRC permettant les opérations multicanaux lorsque l'intervalle de fonctionnement est divisé en alternance entre les intervalles du canal de contr*ô*le (CCH) et du canal de service (SCH). La bande passante de chaque canal est donc divisée par deux. Le but de nos travaux est de fournir suffisamment de fiabilité en temps réel pour les messages ayant trait *à* la s*û*reté du canal de contr*ô*le tout en optimisant les services du canal de service (SCH). Contrairement *à* l'approche qui attribue un intervalle statique pour le canal d'erreur par défaut, nous dveloppons un algorithme dynamique d'ajustement du canal basé sur la théorie itérative du contr*ô*le afin de résoudre le probl*è*me. Nous développons des mod*è*les pour la diffusion *à* large échelle et la diffusion unilatérale afin d'explorer les interconnexions entre la densité du trafic (congestion) et le ratio de la perte de paquets. De plus, nous discutons de l'importance de choisir un intervalle optimal pour le canal et nous apportons un éclairage nouveau concernant le choix adaptatif d'une approche par acc*è*s de canaux qui maximise l'utilisation du canal. Des analyses thoriques exhaustives et des simulations démontrent que nos mod*è*les sont précis, que l'algorithme est efficace et converge vers la solution optimale.

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Last but not the least, I would like to thank my parents Donglin Xiong and Zhiying Xu, for giving birth to me at the first place and supporting me spiritually throughout my life.

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List of Acronyms

16-QAM	16-point Quadrature Amplitude Modulation
64-QAM	64-point Quadrature Amplitude Modulation
AIFS	Arbitration Inter-Frame Space
BPSK	Binary Phase Shift Keying
CCH	Control Channel
CCHI	Control Channel Interval
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
DIFS	DCF Interframe Space
DSRC	Dedicated Short Range Communications
DCF	Distributed Coordination Function
EDCA	Enhanced Distributed Channel Access
ETC	Electronic Toll Collection
FCC	Federal Communications Commission
GPS	Global Positioning System
IETF	Internet Engineering Task Force
IP	Internet Protocol
MAC	Medium Access Control

OBU	On-Board Unit
OFDM	Orthogonal Frequency-Division Multiplexing
PHY	Physical (Layer)
PLR	Packet Loss Ratio
PDR	Packet Delivery Ratio
QPSK	Quadrature Phase Shift Keying
RSU	Road Side Unit
RTS	Request To Send
SCH	Service Channel
SCHI	Service Channel Interval
SIFS	Short Interframe Space
TTL	Time To Live
UTC	Coordinated Universal Time
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2P	Vehicle-to-Pedestrian
VSC	Vehicle Safety Communication Consortium
VANET	Vehicular Ad-Hoc Network
WAVE	Wireless Access in Vehicular Environment
WBSS	WAVE Basic Service Set
WiFi	IEEE 802.11 Wireless LAN Standards
WSA	WAVE Service Announcement
WSM	WAVE Short Message
WSMP	WAVE Short-Message Protocol

Chapter 1

Introduction

1.1 Overview

Traffic accidents and highway congestion are ongoing issues across the world. Unless special actions are taken, road injuries are foreseen to become the fifth leading cause of death by 2030. Globally, road crashes cost USD $518 billion each year, which composes 1%-2% of the annual GDP per country. To tackle this issue, the United States (U.S.) Department of Transportation (DoT), together with industrial companies such as General Motors (GM) and Toyota, are focusing on developing the Dedicated Short-Range Communication (DSRC) standard to facilitate collision prevention applications including lane-changing assistance, road caution hazard notification, etc. [30]. Figure 1.1 shows a primitive demo of a DSRC on board unit (OBU) by GM. In order to enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, intelligent radio devices as radar, lidar, camera are currently in development. The lower level standards, i.e., physical layer protocol and MAC layer protocol, of DSRC have been established and approved by the Federal Communication Commission (FCC) and are at present being revised by IEEE 802.11p task group [20]. The latest amendment known as IEEE 1609.4 heralds that the era for DSRC is fast approaching.

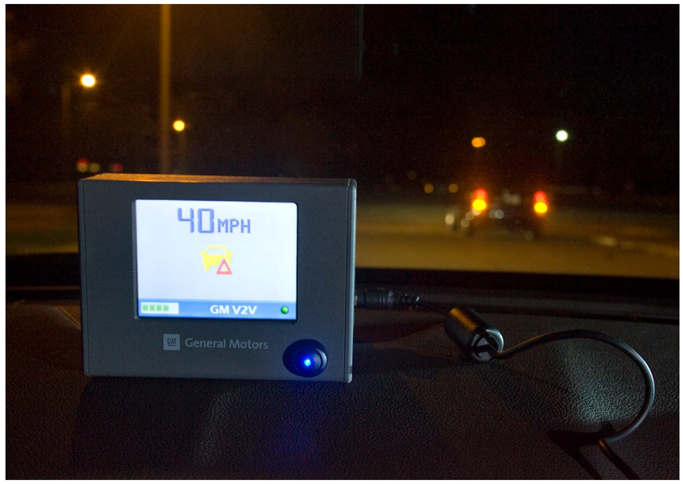


Fig. 1.1 General Motors DSRC system [22]

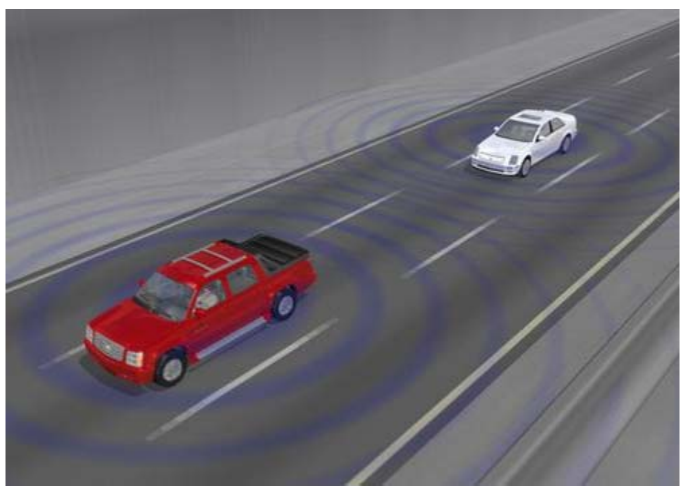


Fig. 1.2 DSRC vehicle-to-vehicle communication [12]

Figure 1.2 shows one scenario of V2V communication. Two vehicles exchange safety and position information via on-board units (OBUs). If a crash seems imminent, e.g. when inter-vehicle distance is too short, the cars will warn their drivers. Normally, the communication range can be as far as 450 m, which is adequate to detect nearby traffic conditions. Figure 1.3 is an initial deployment of DSRC V2I system by USDOT in Michigan state [43]. The Test Bed is located on 75 miles of highway and arterial roadway located in Oakland County, Michigan. The Test Bed is equipped with 52 Dedicated Short Range Communications (DSRC) road side units (RSU) units. The DOT places RSUs to make radio ranges of RSUs overlap each other in order to see how vehicles and the system interact with multiple RSUs.

Fig. 1.3 USDOT recently sets up a Test Bed testing DSRC OBUs and RSUs in Michigan state [43]

Though the primary goal of DSRC is to ensure safe driving, the standard also supports a variety of non-safety related applications from electronic toll collection (ETC), drive-thru to multimedia downloading. The support of non-safety related communications offers a large pool of commercial opportunities which make DSRC devices more cost-effective. In this case, automobile manufacturers are motivated to equip their new vehicles with multi-service enabled DSRC radios. The potential profit of DSRC protocol encourages a greater market penetration.

Wireless Access in Vehicular Environments (WAVE) 1609.4 [2], an extension of DSRC, defines the multi-channel operation. The purpose of this extension is to ensure that multi-radio devices can communicate with each other on the right channel. There are seven channels defined in this extension. One channel known as Control Channel (CCH) is allocated to transmit safety related messages as well as WAVE control messages. The other six channels named Service Channels (SCHs) are reserved for non-safety communication. The extension further defines a division of time intervals into alternating CCH intervals (CCHI) and SCH intervals (SCHI) for single-radio devices [10]. A guard interval is also added in front of each interval to account for time inaccuracies and operational delay. Therefore, devices switch back and forth between CCH and SCH on a Time Division Multiple Access (TDMA) basis. Recently, voices from industry [30] suggest that safety messages should be transmitted on a dedicated channel without time division. Vehicles that are interested in both safety and non-safety data on dedicated channels have to be equipped with at least two radios, one consistently tuned to the safety channel and another involved in WAVE 1609.4 switching. At the initial deployment phase of DSRC, both types of devices will likely appear as there is a tradeoff between radio cost and service quality. Hence, algorithms designed to enhance the performance of the protocol should be comfortable to cope with either scenario.

1.2 Problem Definition

While supporting both safety and non-safety applications, channel switching also brings novel characteristics to 802.11p. First of all, it is mandatory that safety messages are generated in CCH interval to prevent potential *Synchronized Collisions* [13]. Second, transmission medium for a channel has to be declared as busy when the channel is not operating. Thus, no packet from this channel can be transmitted during that time. Third, if the back-off process has not yet completed at the end of the channel interval, it should be frozen and must be restarted when the next channel interval begins.

Furthermore, there are four channel access options defined in the 1609.4, namely continuous access, alternating access, extended access and immediate access, as Figure 2.2 demonstrates. With continuous access, a radio is always tuned to a CCH or SCH. Alternating access is the default channel access approach which equally divides the synchronization interval between CCH and SCH. The drawback of this option is significant as the channel capacity is halved. Safety messages can not be transmitted during SCH interval (SCHI) and non-safety services are not available during CCH interval (CCHI). Additionally, as backoff process in one channel has to be frozen if we do not operate on that channel, packets in the queue associated with that channel will suffer extra delay [37]. Extended Access allows vehicles to stay on SCHs for successive synchronization intervals without switching to CCH. Immediate access allows radios to perform channel switching at any time. Channel capacity could be improved in this approach. However, it still remains an open issue on how to determine the switching point for better reliability and performance. In this work, we focus on how to adaptively adjust the channel interval to balance CCH packet loss and SCH throughput.

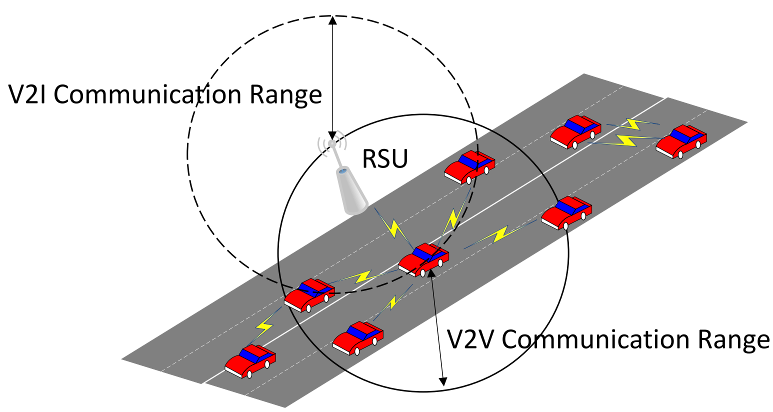


Fig. 1.4 V2V and V2I highway scenario

Current research mainly focuses on modelling continuous access based 802.11 protocol while there is little work concerning channel switching. Moreover, the default channel access approach, alternating access, adopts a fixed channel interval, which can not cope with dynamic scenarios of safety and non-safety applications. In a highway scenario, the network topology is unstable due to the high mobility of vehicles. Fixed channel switch can not not maximize the chance for successful data exchange in V2V or V2I communication, which is a critical flaw hindering DSRC commercialization.

In this thesis, we assume that Road Side Unit (RSU) will be present to provide infotainment applications to vehicles. Hence, we have to guarantee the successful infotainment transmission within small contact time between RSU and nodes. Moreover, once a DSRC network is deployed, it is assumed that main parameters remain constant except traffic densities. The problem that how to divide the operating interval to balance PLR in CCH and throughput in SCHs is what we focus. We propose a multi-channel coordination algorithm based on Markov Chain (MC) to tackle this problem. We take traffic densities as a feedback signal to our algorithm. Our models capture the relationship between packet loss ratio and traffic density. When the density is high, the CCH channel interval will be increased to provide more bandwidth for safety messages. If the density is small, the CCH interval will be reduced ato increase the throughput of non-safety services in SCHs. As a result, These operations allow the CCHI to adapt to dynamic scenarios.

1.3 Thesis Contributions

There are three main contributions of this thesis:

1. We improve previous models on 802.11 EDCA protocol [9] [52] [51], to capture the features of channel switch. The models explore the relationship among traffic density, CCH packet loss ratio, SCH throughput, and the duration of each kind of intervals.

2. We propose an iterative control based multi-channel coordination algorithm, to dynamically adapt channel intervals according to the instant traffic density.

3. We conduct extensive simulations and show that the proposed algorithm almost doubles throughput in SCHs in low traffic density scenario and reduces packet loss ratio up to 30% in high traffic density scenario.

It is worth noting that the proposed algorithm works with both single radio and multi-radio devices. Therefore there is no hardware dependency for our algorithm. This feature is quite beneficial for automobile manufacturers in the early stage of DSRC deployment. To the best of our knowledge, this is the first work that models the reliability of WAVE 1609.4 protocol and dynamically adjusts channel interval without modifying the existing standard.

1.4 Thesis Structure

The rest of this thesis is organized as follows. The related work is introduced in Chapter II; Performance metrics and Markov Chain models for WAVE 1609.4 multi-channel operation in both broadcast and unicast modes are presented in Chapter III; The multi-channel coordination algorithm is discussed in Chapter IV; Chapter V conducts extensive simulations to validate the accuracy of the model and effectiveness of the proposed algorithm; Chapter VI closes this thesis with concluding remarks.

Chapter 2

Related Work

In this chapter, we first briefly introduce the DSRC protocol and IEEE 1609.4 amendment. Then we review related research papers that focus on enhancing the performance and reliability of the DSRC protocol.

2.1 Introduction to DSRC Standard

The Dedicated Short-Range Communication (DSRC) protocol is a short-range wireless communication protocol that offers fast and reliable data transfer in vehicular ad-hoc network (VANET) [6]. The main characteristics of VANET are the high topological dynamics and the infrastructure absence such as access point or base stations existing in the Wi-Fi, WiMax. Moreover, it also introduces new challenges in comparison to traditional wireless networks. First, the high mobility in VANET requires a protocol that can can support fast communications among vehicles. Second, interference from other hot spots is detrimental to real time vehicle communication. DSRC is well designed to solve these two problems: it provides immediate establishment of communication and it is allocated in a dedicated frequency band [19]. Governments have shown great interests in this emerging technology. Table 2.1 summarizes the differences of this protocol in European Union and United States and Table 2.4 compares DSRC with traditional Wi-Fi technology.

Table 2.1 DSRC Standard in Europe and U.S.

	European Union	United States
International Standard	ITU-R M.1453-2 (Layer-1) ISO 15628 (Layer-2,7)	ISO 21215 (CALM M5)
Radio Frequency	5.8 GHz	5.9 GHz
Frequency Range	5.85-5.925 GHz	5.855-5.905 GHz
Downlink rate	500 Kbps	2 - 27 Mbps
Uplink rate	250 Kbps	2 - 27 Mbps
Communication rage	up to 5m	up to 1000m

The spectrum of DSRC is divided into seven channels, namely, one control channel (CCH) and six service channels (SCHs), each of which has 10 MHz bandwidth. In a single radio device, it is supposed to support both kinds of channels. DSRC shall schedule it on a TDMA basis. In dual-radio devices, one radio is always tuned to CCH and another radio is always tuned to SCH. The physical layer of DSRC is similar to that of IEEE 802.11a, which utilizes the Orthogonal Frequency Division Multiplexing (OFDM) technique. The MAC layer utilizes IEEE 802.11p, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). For safety applications, broadcast packets are transmitted via CCH. For non-safety applications, as different user has different demands, it is supposed to use unicast to transmit via SCH. Moreover, to overcome hidden terminals, Request-To-Send (RTS)/Clear-To-Send (CTS) packets are also included in the standard.

There are a number of important applications of DSRC. We summarize safety applications in Table 2.2 and non-safety applications in Table 2.3.

Figure 2.1 presents a layered DSRC architecture. It also follows the seven layer architecture in the OSI model. Besides, new amendments called IEEE 1609 family [2] are

Table 2.2 Safety Applications

Intersection Collision Avoidance	**Public Safety**	**Sign Extension**
Traffic Signal Violation Warning	Approaching Emergency Vehicle Warning	In-Vehicle Signage
Blind Merge Warning	Emergency Vehicle Signal Pre-emption	Curve Speed Warning
Left Turn Assistant	SOS Services	Low Parking Structure Warning
Intersection Collision Warning	Post-Crash Warning	Wrong Way DriverWarning

Table 2.3 Non-Safety Applications

Traffic Management	**Information from OtherVehicles**	**Tolling**
Intelligent On-Ramp Metering	Cooperative Glare Reduction	Drive-thru payment
Intelligent Traffic Flow Control	Instant Messaging	Parking lot payment
Traffic information	Adaptive Headlamp Aiming	Free-Flow Tolling
Infrastructure-based traffic management probes	Adaptive Drivetrain Management	

proposed to enhance DSRC's performance. IEEE 1609.2 addresses security and privacy issues. IEEE 1609.3 defines networking layers. IEEE 1609.4 is a sub MAC layer that rules multi-channel operation and is the main focus of this thesis.

Table 2.4 Comparison of Wireless Technologies

	DSRC	Wi-Fi
Frequency band	5.9 GHz	5/2.4 GHz
Channel Bandwidth	10MHz	20MHz
Supported Data Rate	3,4,5,6,9,12,18,24	6,9,12,18,24,36
Modulation	BPSK, QPSK, 16QAM, 64QAM	Same as DSRC
Channel Coding	1/2, 2/3, 3/4	Same as DSRC
FFT/IFFT Interval	6.4 μs	3.2 μs
Subcarrier spacing	0.15625 MHz	0.3125 MHz
OFDM Symbol	8 μs	4 μs

DSRC is preferred over Wi-Fi because the proliferation of Wi-Fi hand-held and hands-free devices that occupy the 2.4 GHz and 5GHz bands, along with the projected increase in Wi-Fi hot spots and wireless mesh extensions can cause intolerable and uncontrollable levels of interference for vehicular safety applications [47]. DSRC is developed primarily

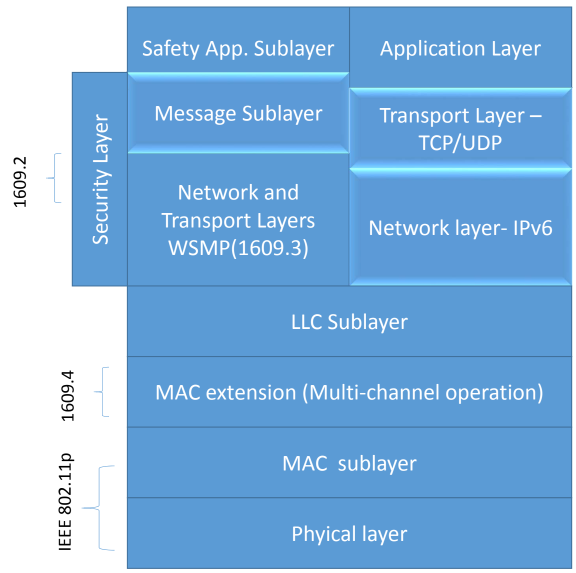


Fig. 2.1 DSRC layered architecture in the United States

for safety applications and addresses the interference issues. Moreover, DSRC is the most important short-range wireless technology today in vehicular networks that provides fast network handover, low latency, high reliability and good security.

2.2 IEEE 1609.4 Standard Overview

The IEEE 1609.4 is a MAC extension that supports multi-channel operations in DSRC. It allows devices to tune to the same channel at the same time. The "rendezvous" channel known as Control Channel is allocated to transmit safety related messages as well as WAVE control messages. Six channels named Service Channel in DSRC spectrum are reserved for non-safety communication. The extension further defines a division of operating intervals into CCH intervals and SCH intervals. A guard interval is also added in front of each interval to account for time inaccuracies and operational delay. Effectively, devices switch back and forth between CCH and SCH on a TDMA basis.

Recently, voices from industry [30] suggest that safety messages should be transmitted on a dedicated channel without involving time division. For vehicles that are interested in both safety and non-safety data, this change entails equipping vehicles with at least two radios, one consistently tuned to CCH and another involving in WAVE 1609.4 switching. At the initial deployment phase of DSRC, both types of devices will likely appear as there is a tradeoff between radio cost and service quality. Hence, algorithms designed for enhancing the performance of the protocol should be comfortable coping with either scenario.

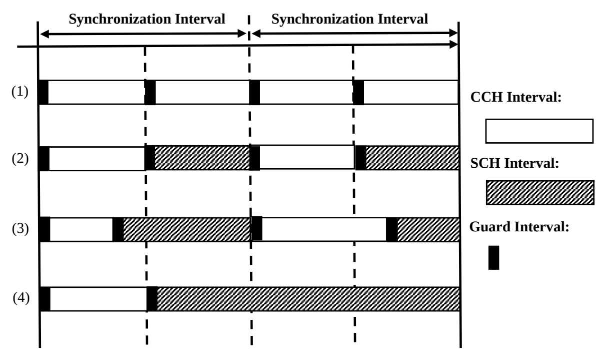


Fig. 2.2 Four channel access options: (1) Continuous Access (2) Alternating Access (3) Immediate Access (4) Extended Access [2]

In terms of channel coordination, there are four channel access options defined in the 1609.4, namely continuous access, alternating access, immediate access and extended access, as figure 2.2 demonstrates. According to continuous access, a radio is always tuned to a CCH or SCH without any switching performed. Alternating access is the default channel access approach which equally divides the whole synchronization interval (100 ms) for CCH and SCH. Immediate access allows radios to perform channel switching at any time. Channel capacity could be saved in this approach. Extended access allows vehicles to stay on SCH for successive synchronization intervals without switching back to CCH.

2.3 Analytical Models of DSRC Multi-Channel Operation

Motivated by problems brought by wireless network dynamics, a number of works address the issue of modelling 802.11 MAC protocol in general such as [9] and in particular for vehicular networks such as [52] [11]. Bianchi [9] first models 802.11 DCF using Markov Chain. Wang et al. [48] study the performance and throughput of a IEEE 802.11p like MAC protocol based on Bianchi's model. While time for transmitting safety related messages in CCH is calculated, the safety message broadcast is not analysed and dynamic switch between CCH and SCH is excluded in the model. Yao et al. [52] further propose a model for 802.11p EDCA protocol. In this paper, priority of different traffic classes and virtual collisions are considered. However, these models only work with the single channel operation. Campolo et al. [11] leverage the Bernoulli process to model prioritized broadcasting in multi-channel vehicular networks. In their paper, the time to live (TTL) of each safety-related message is assumed to be 100 ms, implying that packets failing to be sent in the current synchronization cycle shall be discarded. Nonetheless, this assumption does not reveal the general scenario defined by the standard where packets can be stored in queue and transmitted in next synchronization interval. Moreover, hidden terminals are not considered and the unicasting in SCHs is not modelled. Misić et al. [41] analyse the delay of 802.11p network with single channel devices. Several traffic combinations are accounted for both CCH and SCH. The impact of the interruption of the backoff process by inactive channel time is quantitatively analysed. However, synchronized collision is not captured in the model. This model also grounds the selection of optimal CCH interval according to the policy of the network operator.

Though 802.11 protocols have been extensively explored, a model that fully characterizes the DSRC multi-channel network is still left blank. To this end, we improve previous

DSRC models in multi-channel context. The analytical models embrace following features: (1) both broadcasting safety-related messages in CCH and unicasting non-safety-related services in SCHs are included in the model; (2) impact brought by channel switching is explicitly revealed; (3) metrics like PLR and throughput are adopted to evaluate the system's performance; (4) both saturated and non-saturated network conditions are covered by the model.

2.4 Algorithms Improving DSRC Performance and Reliability

Existing work shows that the default alternating channel access option in multi-channel environment neither provides sufficient reliability for safety-related message delivery [13] [53] nor satisfactory throughput for infotainment services delivery [49] [44]. Techniques to solve this problem have been broadly studied. Kenney et al. [26] propose a new design of WAVE 1609.4 protocol, which includes an extra bit in the packet header to show the nodes' intention to keep staying on CCH or to operate on multi-channels. This work enables the co-existence between single radio nodes and multi-radio nodes and guarantees the reliability of safety related messages. D. Jiang et al. [17] introduce a "peercast" protocol to enable vehicles to asynchronously switch channels. In this paper, vehicles are not required to receive all safety messages to guarantee reliability. Thus, they can selectively listen to CCH, hence, spend more time in SCH. Tony et al. [36] propose a multi-channel MAC protocol that leverages a Road Side Unit (RSU) to coordinate channels and differentiate distances to service coverage area. Kai et al. [31] and Han et al. [14] also shed insights on how to design a multi-channel MAC protocol to minimize collision. Wang et al. [48] adjust the CCH time interval by quantitatively calculating the time required to send safety messages, hence SCH throughput may change accordingly. Nonetheless, this is a static approach that does not explicitly guarantee reliability. Moreover, time synchronization problem is not appropriately handled. To summarize, there is no analytical model that includes both basic features of IEEE 802.11p and WAVE 1609.4 multi-channel protocol. In addition, there is also no dynamic solution that adjusts the interval length to meet requirements of reliability and throughput in multi-channel environment.

In order to tackle these challenges, we propose a multi-channel coordination algorithm that is based on the feedback signal of current reliability, which is calculated based on the proposed models. For every interval update period, if the reliability is detected as "low", CCH intervals will be enlarged to alleviate synchronized collision. Conversely, if the reliability is higher than a pre-defined threshold, CCH intervals will be reduced to give more time for infotainment services transmission in SCHs. Our algorithm properly handles time synchronization between vehicles and works well with the existing standard.

2.5 Summary

In this chapter, we briefly introduce basics of DSRC protocol as well as its newest amendment IEEE 1609.4. We also review existing work on analytical models of IEEE 802.11 MAC protocol and algorithms to improve the performance and reliability of DSRC. Finally, we show there are still challenges in providing satisfactory reliability and throughput in multi-channel operation, to which end we propose new analytical models and a multi-channel coordination algorithm.

Chapter 3

Analytical Models of 1609.4 Broadcasting and Unicasting

Performance and reliability analysis of the IEEE 802.11p MAC layer is an important and challenging problem that attracts considerable amount of attention from researchers. However, many existing works only address basic features of IEEE 802.11p. The newly proposed standard IEEE 1609.4 which supports multi-channel operations has not been fully explored and the synchronized collision introduced by multi-channel operations has not yet been analysed. In this chapter, we assume safety messages are broadcasted in CCH and non-safety related messages are unicasted in SCH. This assumption is based on the fact that safety messages are used to alert all vehicles nearby and non-safety related messages such as MP3 downloading are specific to a vehicle. We elaborate analytical models for both scenarios. Besides the fundamental EDCA MAC protocol, we also consider the 1609.4 MAC sub-layer extension. Metrics showing the performance and reliability of the system are also derived based on proposed analytical models.

3.1 Assumptions

In this chapter, we focus on the reliability and performance analysis of the broadcasting in CCH and unicasting in SCHs. We consider each vehicle as a node in our model and several practical factors that impact the performance of DSRC radios. In our models, we assume IEEE 802.11p and IEEE 1609.4 work under following scenarios.

1. The instant positions of vehicles follow a Poisson distribution on a single lane. This assumption has been verified with real-world data in [21]. Thus, Given the traffic density β, the probability $P(i,l)$ of finding i nodes in length l is

$$P(i,l) = \frac{(\beta l)^i e^{-\beta l}}{i!}. \tag{3.1}$$

2. Packet arrivals at each node follow a Poisson process with arrival rate λ. And the packet service time at each node follows a general distribution. Therefore, the buffer at each node can be modelled as a M/G/1 queue.

3. All nodes have the same transmission range, R. The mean number of nodes within transmission range of a tagged node is $N_{tr} = 2\beta R$.

4. All nodes have the same carrier sense range, L_{cs}, the mean number of nodes within the carrier sensing range of the tagged node is $N_{cs} = 2\beta L_{cs}$.

5. We assume that CCH and SCHs adopt the same modulation technique to ensure that their transmission ranges are identical.

6. As is shown in Figure 3.2, the potential hidden terminal areas of the tagged node are $[L_{cs}, R + L_{cs}]$ and $[-R - L_{cs}, -L_{cs}]$. We assume L_{cs} equals to the interference range L_{int}, the average number of potential hidden nodes is $N_{ph} = 4\beta R$.

7. We neglect the Doppler shift caused by the mobility of vehicles . According to [33], vehicles with a speed of 120 mi/h will only move 0.053m during a packet transmission time (packet size is 200B and data rate is 12Mb/s). It is orders of magnitude smaller than the lane length.

8. We assume that RTS/CTS scheme is turned off in our scenario to minimize communication overhead.

9. We consider all traffics are of the same access class.

3.2 Markov Chain Model for 802.11p Broadcast in CCH

This model improves previous models as it includes both channel switch and synchronized collision. The states of our Markov Chain model are a set of possible backoff counters, denoted as $\{b(t)\}$. The backoff counter down-counts the number of idle time slots that a node has to wait before transmission. If the counter reaches zero, it entails that the node is ready to transmit. Moreover, as there is no feedback acknowledgement from the receiver if the packet is successfully transmitted or not, the transmitter does not have any idea about the network condition. Hence, the contention window will be kept constant. We model this process as a 1-D Markov Process as Figure 3.1 illustrates. In Figure 3.1, IDLE is the state that there is no packets ready to be sent. The states $\{0, ..., W_0 - 1\}$ denote the value of the backoff counter. p_b is the probability that the node senses other nodes occupying the channel. p_{cch} is the probability that CCH is the current operating interval. p_{sch} is the probability that SCH is the current operating interval.

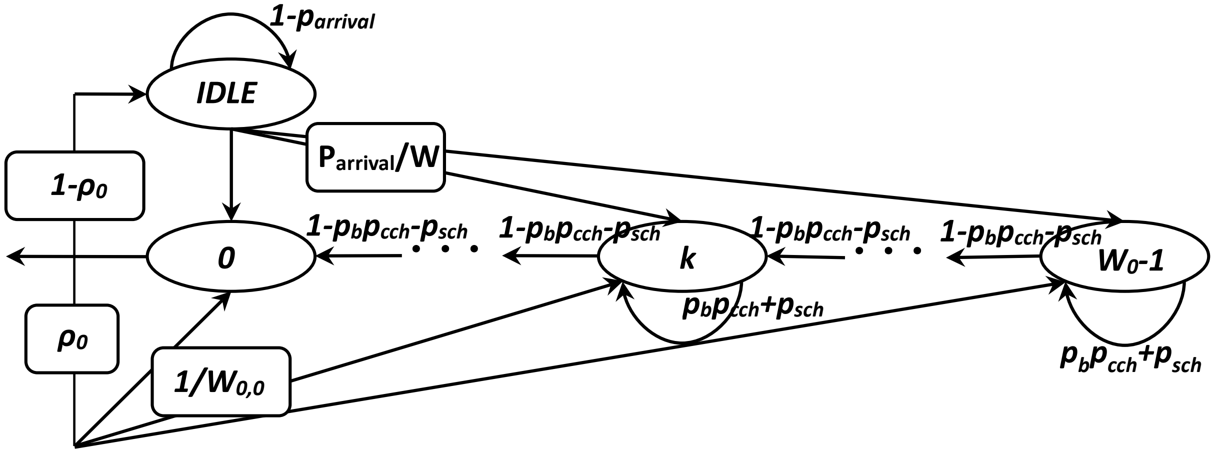


Fig. 3.1 1-D Markov Chain for Control Channel improved over the EDCA model in paper [52]

3.2.1 Stationary probability

We first would like to know the stationary probability of each states. Let π_k be the stationary probability of state $\{b(t) = k\}$ and π_{IDLE} be the stationary probability of state *IDLE*, i.e. when there is no packet running the backoff process. We have following balance equations between states:

$$\pi_{IDLE} = \frac{1-\rho}{P_{arrival}}\pi_0, \tag{3.2}$$

$$\pi_k = \frac{W_0 - k}{(1-p)W_0}\pi_0, \tag{3.3}$$

where ρ is the packet queue utilization in CCH and $\rho = min(1, \frac{\lambda_{CCH}}{\mu_{CCH}})$.

3.2.2 Blocking probability

Next, we derive the blocking probability in the MC in order to get an analytical solution. Since the backoff process will be blocked when the medium is sensed *busy*, which includes two cases, either the node detects there is a transmission on going in CCH or the operating interval is in SCHs. The overall blocking probability is

$$p = (1 - \frac{T_{CCHI}}{T_{SYNC}}) + \frac{T_{CCHI}}{T_{SYNC}} p_b, \tag{3.4}$$

where p_b is the probability that a node finds an on going transmission in CCH, T_{CCHI} is the CCH interval and T_{SYNC} is synchronization interval.

Since the packet arrival rate follows a Poisson distribution, the probability that a packet arrives in a generalized slot time is

$$P_{Arrival}^{CCH} = \sum_{k=1}^{\infty} \frac{(\lambda_{CCH}\sigma'_{CCH})^k}{k!} e^{-\lambda_{CCH}\sigma'_{CCH}} = 1 - e^{-\lambda_{CCH}\sigma'_{CCH}}, \tag{3.5}$$

where an average slot time is

$$\sigma'_{CCH} = p_b T' + (1 - p_b)\sigma, \tag{3.6}$$

where σ is a normal time slot and T' is the average time that the backoff counter will be fronzen when the channel is sensed busy, which is

$$T' = \frac{L_H + \mathbb{E}[P]}{R_d} + DIFS + \delta, \tag{3.7}$$

where L_H is the packet header, $\mathbb{E}[P]$ is the packet length, R_d denotes the data rate, δ represents the propagation delay and $DIFS$ is the Distributed Inter-frame Spacing in the 802.11 protocol. Summing up all stationary probabilities in the Markov Chain, we have

$$\pi_{IDLE} + \sum_{k=0}^{W_0 - 1} \pi_{kj} = 1. \tag{3.8}$$

Thus, the stationary state probability π_0 is

$$\begin{aligned}
\pi_0 &= [\frac{W_0+1}{2(1-p)} + \frac{1-\rho}{p_{arrival}}]^{-1} \\
&= [\frac{W_0+1}{2\{1-[1-\frac{T_{CCHI}}{T_{SYNC}} + \frac{T_{CCHI}}{T_{SYNC}}(1-e^{-\pi_0(N_{cs}-1)})]\}} \\
&\quad + \frac{1-\rho}{1-e^{-\lambda_{CCH}\sigma}}]^{-1}.
\end{aligned} \tag{3.9}$$

Also, as it models the broadcast mode, this is also probability, τ_{CCH}, that any node transmits in an arbitrary time slot.

3.2.3 Service Time

It is critical to know the service time as we need it later to find the queue utilization. Arrival process is modelled as a Poisson process and we characterize the service time as a general distribution. Hence, each node works as a M/G/1 queue. Denote q_i as the steady state probability that the service time is i time slots. Let $Q(z)$ be the *Probability Generating Funtion (PGF)* of q_i and it can be represented as,

$$Q(z) = \sum_i q_i z^i. \tag{3.10}$$

Its first order derivative is the service time that we are looking for.

3.2.4 Modelling CCH and SCH Channel Switching

CCH and SCH channel switching is a new feature that we shall include in our model. Each synchronization interval is divided into a CCH interval and a SCH interval. There are separate backoff counters in each channel. How to integrate different channels into one model remains a problem. We understand that the backoff counter in each mobile node will be decremented by a slot once an idle channel is sensed for a DCF Interframe Space (DIFS). Conversely, it will wait for an extra period once the channel is sensed busy. Moreover, if the backoff starts near the end of CCHI, there is a high likelihood that it can not be completed within this interval. As a penalty, it has to wait for a period of SCH interval and guard interval. When the next cycle comes, it will be unblocked and continue the backoff process. As it is mentioned in Section III-A, the probability that a node waits for two consecutive cycles approaches to zero even when there is a congestion in the network [40]. Otherwise the the queuing delay will be too long to satisfy real-time requirement. Therefore, for a tagged transmitting node in broadcast communication, the time for the backoff counter decrementing by one can be modelled by the following PGF

$$\begin{aligned} H_{total}(z) = &(1 - e^{-\lambda_{CCH}(CCHI-T)})[(1-p_b)z + p_b z^{\frac{T}{\sigma}}] \\ &+ e^{-\lambda_{CCH}(CCHI-T)} z^{\frac{SYNC-CCHI}{\sigma}}((1-p_b)z + p_b z^{\frac{T}{\sigma}}). \end{aligned} \quad (3.11)$$

Hence, the PGF of the service time is obtained from the product of the PGF of the backoff decrementation time and the transmission time, which is

$$Q_{total}(z) = \frac{z^{\frac{T-DIFS}{\sigma}}}{W_0} \sum_{i=0}^{W_0-1} (H_{total}(z))^i. \quad (3.12)$$

As a result, the first moment of the service time can be calculated from the above PGF which is in the following form

$$T_{total}^{ave} = \sum_{i}^{\infty} q_i = \frac{dQ_{total}(z)}{dz}|_{z=1}. \quad (3.13)$$

By definition, the service rate of the queue is achieved as

$$\mu_{CCH} = \frac{1}{T_{total}^{ave}}. \tag{3.14}$$

3.2.5 Numerical Estimation

After building the above model, we can numerically quantify the service rate, service time and packet transmission probability in an arbitrary slot. To calculate the service rate, we have to know the queue utilization ρ. However, ρ itself is a function of μ_{CCH}. Thus, we need to apply the following iterative method to solve equations from (3.9) to (3.14).

Step 1 Initialize ρ based on the estimation of the network condition, i.e. If the network is unsaturated, it is better to initialize the value with 0.

Step 2 Solve the multivariate nonlinear equations which are composed by equation (3.9), (3.11), (3.12) and (3.14).

Step 3 Calculate the average service rate according to equation (3.14).

Step 4 ρ_{0new}=$min(\lambda_{CCH} T_s, 1)$. If $\rho_{0new} - \rho < \epsilon$, the iteration is completed, where ϵ is a pre-defined error bound. Otherwise, go to Step 2 with ρ_{0new}

Comparing multi-channel operation with single channel operation in IEEE 802.11p, we can quantify the service time caused by channel switching as follows

$$\Delta T = T_{total}^{ave} - T_c^{ave}. \tag{3.15}$$

where T_{ave}^c is the mean service time for 802.11p that operates in continuous access and defined in [35] and $T_{ave}^c = \frac{dQ(z)}{dz}|_{z=1}$.

3.2.6 Packet Loss Ratio

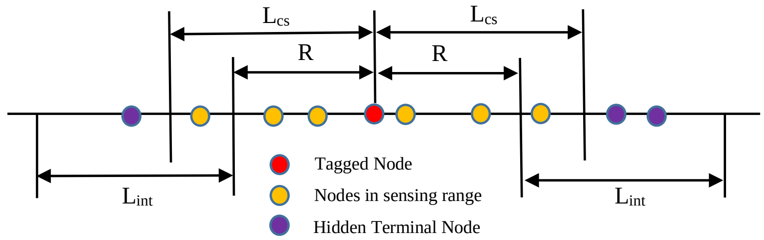


Fig. 3.2 1-D VANET Model [52]

Packet Loss Ratio (PLR) [7] is an indispensable metric quantifying reliability. It can be calculated as a complement of Packet Delivery Ratio (PDR). PLR is defined as the probability of failing to receive a packet at the receiver after this packet is transmitted at the sender. To calculate PLR in a vehicular scenario, we consider a 1-D VANET scenario as shown in Figure 3.2. Both hidden terminals and concurrent transmissions of nodes within carrier-sensing range of the tagged node have negative impact on PLR. Following the approach in [35], we are able to obtain the analytical form of PDR and then get its complement to have PLR. Due to space limitation, we hereby directly present the final results. Please refer to [35] for more detail.

Define $\Delta L = L_{cs} - L_{int}$, $C = \beta T_{vuln} \tau_{CCH}/t_s$, where β is the traffic density, T_{vuln} is the vulnerable period that the transmission suffers from hidden terminal problem and t_s is the average time the transmission takes. From previous sections, we have calculated the probability that a node transmits in an arbitrary time slot, τ_{CCH}, which is the input of the model. We also have the traffic density. Thus, PDR affected by hidden terminal [35] is

$$PDR_h = \begin{cases} 1, \ 0 < d \le \Delta L. \\ 1 - (1 - \frac{\Delta L}{d} - \frac{1}{dC})e^{-(R-d)C} \\ -\frac{1}{dC}e^{-(R-\Delta L)C}, \ \Delta L < d \le R. \end{cases} \tag{3.16}$$

PDR impacted by concurrent collision from right-hand side nodes of the tagged node [35] is

$$PDR_{cr} = \begin{cases} e^{-(\beta L_{int}-1)\tau_{CCH}}[1 - \frac{\frac{1}{\tau_{CCH}} e^{-\beta(\Delta L - d)\tau_{CCH}}}{\beta d} \\ +(1 + \frac{1}{\tau_{CCH}\beta d})e^{-\beta \Delta L \tau_{CCH}}],\ 0 < d \leq \Delta L. \\ e^{-(\beta L_{int}-1)\tau_{CCH}}[1 - (1 - \frac{\Delta L}{d} - \frac{1}{\beta d \tau_{CCH}}) \\ -\frac{\Delta L}{d}],\ \Delta L < d \leq R. \end{cases} \tag{3.17}$$

PDR impacted by concurrent collision from left-hand side nodes of the tagged node [35] is

$$PDR_{cl} = e^{-\beta(L_{int}-\tau_{CCH})}[1 - e^{-\beta(R-d)} \\ + \frac{1}{\beta d \tau_{CCH}} e^{-\beta(R-d)\tau_{CCH}} - \frac{1}{\beta d \tau_{CCH}} e^{-\beta R \tau_{CCH}}]. \tag{3.18}$$

Hence, the final PDR of the system [35] is derived as:

$$PDR_{total} = PDR_h \times PDR_{cl} \times PDR_{cr}. \tag{3.19}$$

As a result, PLR can be calculated as

$$PLR = 1 - PDR_{total}. \tag{3.20}$$

3.2.7 Synchronized Collision

In multi-channel operations, there is a high probability for synchronized collision at the start of a channel interval among devices with ready-to-send packets. All of devices respect the 802.11 back-off rule and select a random back-off slot to avoid collision. However, in this special case, the collision can not be avoided. The main reason behind this problem is that the default contention window is set to 16, which restricts each node to randomly select a back-off time slot within {0,1,2, ... , 15}. If there are more than 16 nodes in the network (which is a common scenario), with probability one, two nodes will select the same time slot to start transmission, thus concurrent collision happens. Moreover, any two nodes will be in the vulnerable period and thus they will still suffer from synchronized hidden terminal problem. Figure 3.4 shows the synchronized collision we observe in NS2 simulation. The MAC layer packets in the red box are transmitted almost in the same time instant, which causes synchronized collision and synchronized hidden terminal packet loss.

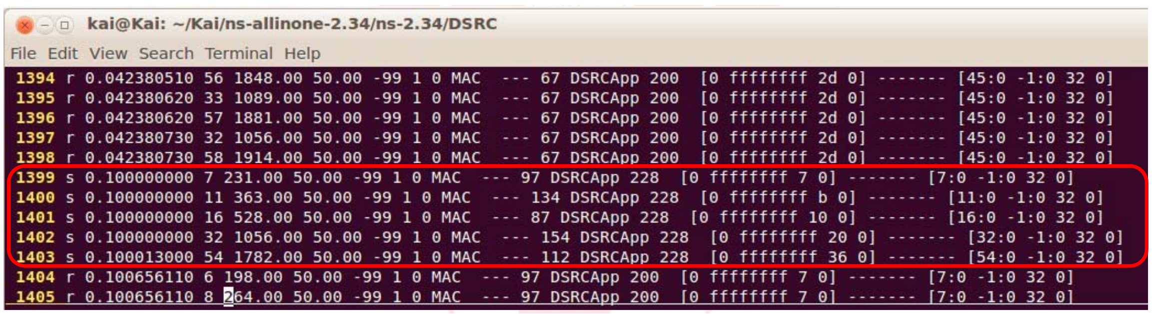


Fig. 3.3 Synchronized collision observed in NS-2 simulation.

This important impact shall be included into our analytical model.

We know the channel utilization is $\rho = \frac{\lambda_{CCH}}{\mu_{CCH}}$. And the probability that a packet is sent in a time slot is τ_{CCH}. Define PLR_{SYNC} as the PLR in the first W_0 slots that mostly impacted by synchronized collision and PLR_{NORMAL} as the PLR after the first W_0 slots that majorly impacted by interference and fading. Thus, the total packet loss in a CCHI is $PLR_{NORMAL} \times (\frac{CCHI}{\sigma} - W_0) \times \tau_{CCH} + PLR_{SYNC} \times W_0 \times \rho$. And the total number of packets sent is $\frac{CCHI}{\sigma} \times \tau_{CCH} + W_0 \times \rho$. Therefore, the overall packet loss rate over a CCHI

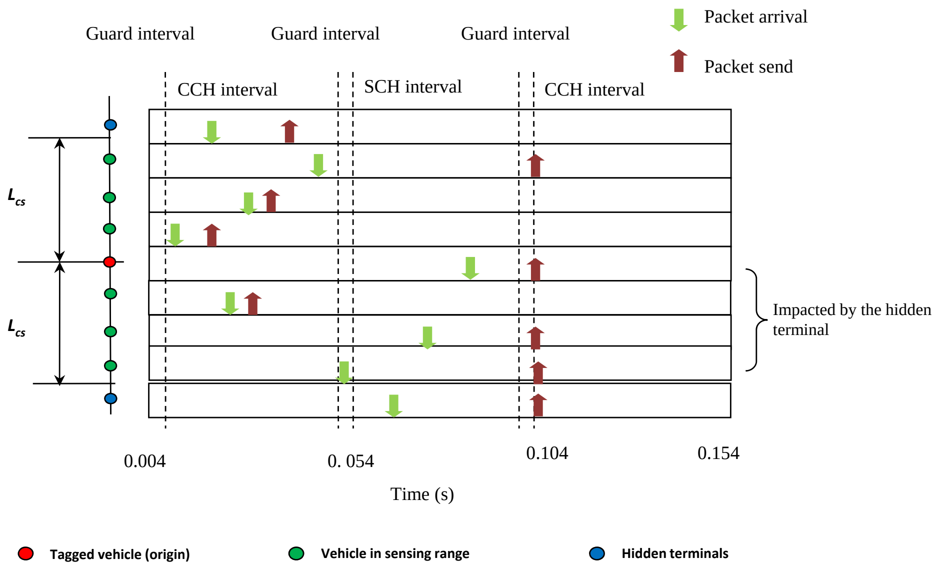


Fig. 3.4 Synchronized collision at start of a channel interval

including synchronized packet loss is

$$PLR_{TOTAL} = \frac{Total\ Packets\ Loss}{Total\ Packets\ Transmitted} \tag{3.21}$$

$$= \frac{PLR_{NORMAL} \times (\frac{CCHI}{\sigma} - W_0) \times \tau_{CCH} + PLR_{SYNC} \times W_0 \times \rho}{\frac{CCHI}{\sigma} \times \tau_{CCH} + W_0 \times \rho}, \tag{3.22}$$

where N is the total number of nodes within the communication range of the tagged node and PLR_{NORMAL} is calculated by the normal packet arrival probability in a slot and PLR_{SYNC} is calculated using the utilization (there is at least one packet in the queue).

Therefore, the average packet loss rate of the tagged node is

$$PLR_{AVG} = \frac{1}{N} \sum_i PLR_i, \tag{3.23}$$

where PLR_i is the overall packet loss ratio of node i with respect to the transmissions from the tagged node.

3.3 Markov Chain Model for WAVE 1609.4 Unicast in SCHs

While in CCH, safety messages are flooded to all neighbors, non-safety services are usually transmitted upon request in unicast mode. In this mode, the sender is aware of the reception of transmitted packets. Once a transmission fails, a retransmission will be scheduled and the contention window will be doubled. Conforming to previous assumptions, we model the backoff process of the transmission as a 2-D Markov Chain with state space {s(t),b(t)}, where s(t) is the backoff stage and b(t) is the backoff counter. Figure 5.6(a) presents the 2-D Markov Chain.

We know the channel utilization is $\rho = \frac{\lambda_{SCH}}{\mu_{SCH}}$. And, the probability that in an generalized time interval a node receives a packet from upper layers,

$$P^{SCH}_{Arrival} = 1 - e^{-\lambda_{SCH}\sigma'_{SCH}}, \tag{3.24}$$

where σ'_{SCH} is an average time slot which is

$$\sigma'_{SCH} = (1 - P_{tr})\sigma + P_{tr}(1 - P_s)T_c + P_t r P_s T_s. \tag{3.25}$$

Moreover, due to channel switching and other nodes' transmission, the probability that the backoff counter gets blocked is

$$P_{uni} = \frac{T_{SCHI}}{T_{SYNC}} P_b + \frac{T_{SYNC} - T_{SCHI}}{T_{SYNC}}, \tag{3.26}$$

where T_{SYNC} is the whole synchronization period.

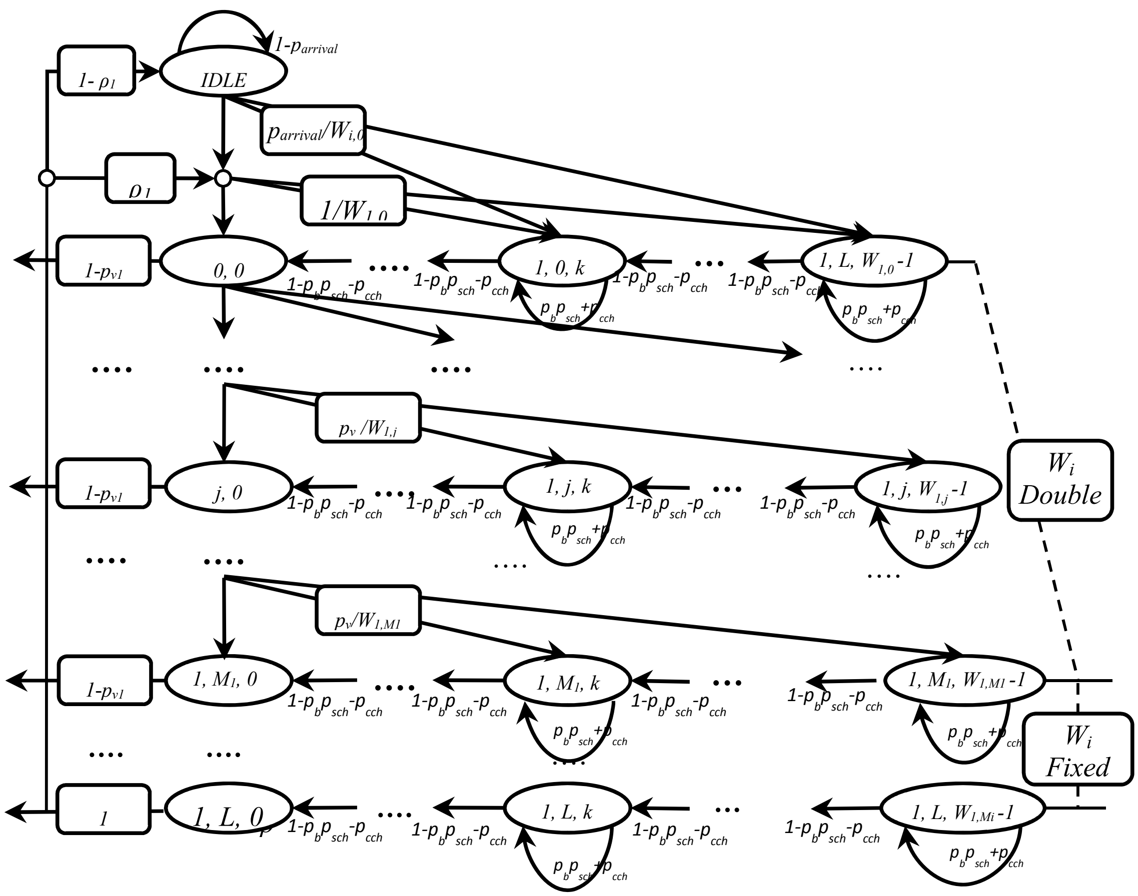


Fig. 3.5 2-D Markov Chain for Unicasting Service Channel improved over EDCA model in paper [52]

Obtain the transition probability from figure 5.6(a) and recall the fact that the sum of all stationary probabilities equals one, we are able to get the stationary state probability $\pi_{0,0}$

$$\pi_{0,0} = \left\{ \frac{\frac{W_0}{2} P_{tr} \left[1 - (2p_{uni})^{m+1}\right]}{(1 - p_{uni})(1 - 2P_{tr})} + \frac{1 - P_{tr}^{m+1}}{(1 - 2P_{tr})} \right. \tag{3.27}$$

$$\left. + \frac{(1 - P_{tr}^{m+1})}{(1 - P_{tr})} + \frac{W_0/2}{(1 - P_{uni})} + \frac{1 - \rho_{uni}}{P_a} \right\}^{-1}, \tag{3.28}$$

where P_{tr} is the probability that there is at least one node transmitting in current slot and is calculated as

$$P_{tr} = 1 - (1 - \tau_{SCH})^{2\beta R+1}, \tag{3.29}$$

and $T_{vuln} = \frac{(L_H + \mathbb{E}[P])}{R_d}$ which is the vulnerable period during which the tagged nodes transmission is vulnerable to hidden terminals. The probability that a transmission is successfully completed is

$$P_s = \frac{(2\beta R + 1)\tau_{SCH}(1 - \tau_{SCH})^{2\beta R}}{P_{tr}}, \tag{3.30}$$

where $T_s = \frac{L_H + \mathbb{E}[P]}{Rd} + SIFS + \sigma + ACK + DIFS + \delta$. T_s is the time period for successfully transmitting a packet. And τ_{SCH} is the probability that a packet is transmitted in an arbitrary time slot

$$\tau_{SCH} = \sum_{i=0}^{m} b_{i,0} = \frac{1 - p_v^{L+1}}{1 - p_v}\pi_{0,0}. \tag{3.31}$$

Following a similar iterative method in section 3.2.5, we can solve ρ_{uni} and $\pi_{0,0}$.

3.3.1 System Throughput

The normalized system throughput [9] [16] is defined as the ratio

$$S = \frac{\mathbb{E}[payload\ information\ transmitted\ in\ a\ slot\ time]}{\mathbb{E}[length\ of\ a\ slot\ time]}, \tag{3.32}$$

which represents the portion of a unit time frame that the channel successfully transmits the payload. $P_{tr}P_s\mathbb{E}[P]$ is the average payload bits transmitted in a slot time. The mean value of a slot time is composed of three parts, namely, a fraction that the channel is idle, a fraction that the channel fails to transmit the packet due to collision and a fraction that the channel is used to successfully transmit the packet. Therefore, we can write the normalized system throughput in following form [9] [16]

$$S = \frac{P_t P_s \mathbb{E}[P]}{(1-P_t)\sigma + (P_t(1-P_s))T_c + P_t P_s T_s}, \tag{3.33}$$

where $T_c = \frac{L_H + \mathbb{E}[P]}{Rd} + DIFS + \delta$ which is the time period the the backoff timer should defer when detecting an ongoing transmission.

3.4 Tradeoff in the models

Essentially, models of PDR in CCH and throughput in SCHs are functions of many parameters. However, most of them have been determined by the DSRC protocol. Suppose the traffic density information is given, the only parameter we can adjust is CCHI. Since the sum of CCHI and SCHI equals synchronization interval, which is a constant, when we increase CCHI, the SCHI is decreased and vice versa. If CCHI is increased, there will be more time for transmissions in CCH. Thus the queue utilization will be small, causing less synchronized collision. The overall PDR will increase as well. However, throughput in SCHs will decrease if CCHI is increased. From the model, we see that the less time for SCHI, the more likely SCH will be blocked. Thus less packets will be sent. This tradeoff gives us the intuition to design an algorithm that can dynamically adjust the channel interval to balance the reliability in CCH and throughput in SCHs. We will provide a detailed design in Chapter IV.

3.5 Summary

In this chapter, we focus on the performance and reliability analysis of IEEE 1609.4 in CCH and SCH respectively. For CCH, we leverage a 1-D Markov Chain (MC) to model broadcasting with no retransmission. In this case, we are interested the reliability of safety communications and use PLR as the reliability metric, where not only concurrent collision and hidden terminal impacts are considered but also the impact of synchronized collision is included. For SCHs, we develop a 2-D Markov Chain model to capture the features of unicasting in SCHs with retransmission. We obtain the analytical result of system throughput in this case. Moreover, this is the first work to include multi-channel operations in the analytical model under realistic assumption. This work also lays the foundation of chapter 4, where we apply these models to derive an effective multi-channel coordination algorithm to well balance the reliability and performance tradeoff in CCH and SCHs.

Chapter 4

Multi-Channel Coordination Algorithm

Ideally, CCH and SCHs shall be operating on different transceivers such that they do not have to share radio resources. And this is the long term goal of DSRC (10-20 years). However, according to C. Campolo [10], dual-radio devices are far more costly than single-radio devices. This leads to much longer time for DSRC to penetrate the market. Another issue for dual radio devices is that one radio would have strong interference on the other if they are physically close regardless of what channel they operate. For these reasons, single-radio devices are the main focus in the initial deployment stage of DSRC. However, the problem that the duration of CCH and SCH is halved in single-radio devices is still critical. To cope with dynamic demands of the reliability in CCH and throughput in SCHs, we propose a multi-channel coordination algorithm to adaptively adjust CCH and SCH intervals. The proposed algorithm maximizes SCH throughput while provisioning sufficient reliability for delay-stringent safety packets. The main idea is to set-up a lower bound of the reliability for safety messages. When traffic density is low, a very small CCH interval can fulfil this demand and the remaining time resource can contribute to non-safety services delivery. On the other hand, when the density is high, we can enlarge CCH interval to provision more time resource to complete the transmission of safety messages in that synchronization interval.

4.1 The Multi-Channel Coordination Algorithm

In this section, we propose the multi-channel coordination algorithm. We view the channel interval as limited resources for safety related messages and non-safety applications. Thus, this problem can be viewed as a Resource Optimization (RO) problem. When dispatching resources, we have to balance the reliability of time-stringent safety services and the performance of infotainment applications. We design an iterative control system to achieve this goal as figure 4.1 shows. We denote PLR as the price function in the RO problem and the Packet Delivery Ratio (PDR) is obtained as 1-PLR. Concerning our primary goal,

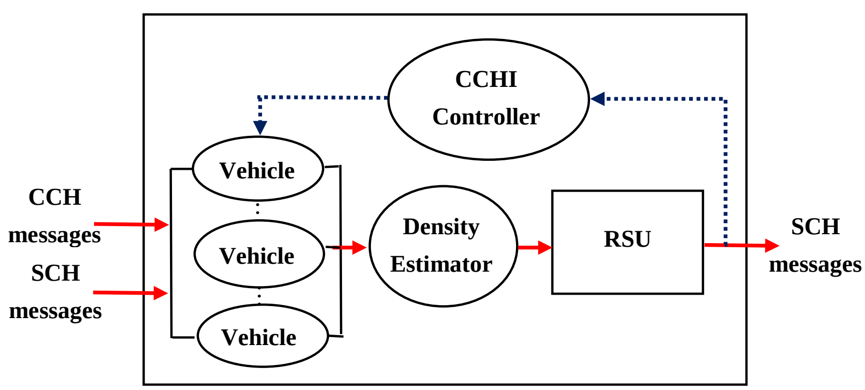


Fig. 4.1 Iterative Control System

guaranteeing the reliability of safety services, CCHI will be enlarged to relieve synchronized collision when the reliability is low, i.e. the on road traffic density is heavy. it will be reduced when the reliability is higher than the pre-defined threshold, i.e. the traffic density is low. The dynamics of CCHI thus is

$$\dot{CCHI} = -\alpha_0(PDR - PDR^{th}), \tag{4.1}$$

where α_0 is a constant, $\alpha_0 > 0$ and PDR^{th} is a pre-defined threshold.

As a result, when CCHI increases, PDR will obviously increase as the synchronized collision is relieved. On the other hand, PDR will decrease when CCHI decreases. In summary, PDR has a positive relationship with CCHI. Dynamics of PDR is therefore

$$\dot{PDR} = \alpha_1(CCHI - CCHI^{th}), \tag{4.2}$$

where α_1 is a constant and $\alpha_1 > 0$.

With equation (4.1) and (4.2), we have

$$\ddot{PDR} + \alpha_0\alpha_1 PDR = \alpha_0\alpha_1 PDR^{th}. \tag{4.3}$$

The damp ratio in this system is 0, according to control theory [15], it exhibits non-decaying oscillations. The interval will not converge to an optimal value. To overcome this problem, a proportional-plus-derivative (PD) controller can be adopted to have a system that converges. *Ergo,* we have the following theorem concerning stability.

Theorem 1 (System Stability) *The proposed control system is stable if $\alpha_0 > 0$, $\alpha_1 > 0$, $\alpha_3 > 0$ and the PD controller*

$$\dot{CCHI}(t-d) = -\alpha_0(PDR(t) - PDR^{th}) - \alpha_3\dot{PDR}, \tag{4.4}$$

is adopted.

Proof: The PD controller can first be constructed as follows

$$C\dot{C}HI = \alpha_0(PDR - PDR^{th}) - \alpha_3 P\dot{D}R. \tag{4.5}$$

And due to delay, d, for information update in the system, the CCHI we used is actually the one at $t - d$

$$P\dot{D}R = -\alpha_1(CCHI(t-d) - CCHI^{th}). \tag{4.6}$$

Eventually, we have the final PD controller,

$$C\dot{C}HI(t-d) = -\alpha_0(PDR(t) - PDR^{th}) - \alpha_3 P\dot{D}R(t). \tag{4.7}$$

After adopting equation (4.4), we have the new dynamic system,

$$P\ddot{D}R + \alpha_1\alpha_3 P\dot{D}R + \alpha_0\alpha_1 PDR = \alpha_0\alpha_1 PDR^{th}. \tag{4.8}$$

It is easy to verify that the two characteristic roots of equation (4.8) have negative real parts, therefore the system is stable. We can finally have the PD controller by using Taylor series to expand equation (4.7) as

$$\begin{aligned} CCHI \quad & (n+1-\tau) && (4.9)\\ = \quad & S\{CCHI(n-\tau) - \lambda(PDR(n) - \\ & PDR^{th}) - \zeta(PDR(n) - PDR(n-1))\}, \\ = \quad & S\{CCHI(n-\tau) - \lambda(PLR^{th} - PLR(n)) \\ & -\zeta(PLR(n-1) - PLR(n))\}, && (4.10) \end{aligned}$$

where

$$S(x) = \begin{cases} 0\ ms,\ if\ x < 0, \\ 100\ ms,\ if\ x > 100, \\ x\ ms,\ otherwise, \end{cases} \tag{4.11}$$

and λ and ζ are step sizes that control the rate of convergence. Once we have the consensus results of the traffic density (to be discussed in the next subsection), we calculate the PLR based on previous calculated CCHI. Moreover, we can obtain the new CCH interval through above PD controller.

Algorithm 1 Mult-channel coordination algorithm

Input: step size λ,ζ, traffic density, PLR threshold;
Output: the updated CCH interval

```
CCHI = 46 ms, SCHI = 46 ms, GuardInterval = 4 ms
Select an optimal update period T_0
for every period of T_0 do
    1. Vehicle side:
        Each vehicle estimates current traffic density and sends it to the associated RSU
    2. RSU side:
        RSUs achieve a consensus on the density based on Distributed consensus algorithm
        RSU calculates PLR based on equation (3.20)
        In next CCH interval, RSU distributes the new CCH length by WAVE Short Message (WSM)
    3. Vehicles side:
        Upon receiving the message, the vehicle will use the new in CCH interval in next synchronization interval.
end for
```

4.2 Algorithm Convergence and Convergence Rate

The iterative control approach is essentially a gradient descent method [23]. We want to have the PLR approach the threshold, thus the reliability is guaranteed regardless of the traffic density. According to gradient descent theory, and as we have PLR as a convex function, ∇ PLR Lipschitz continuous, and appropriate step size ζ, λ, we can guarantee a local solution [23]. Moreover, in this case, the method will eventually converge to a global desired solution. The convergence rate is dependent on the step size ζ, λ. Large step size leads to large update each time, thus it converges faster. Conversely, small step size moves slowly to the solution but it provides higher accuracy. Thus there is a tradeoff. To achieve the best tradeoff we shall dynamically choose the step size. In initial update stage, we choose large step size in order to move fast to the solution. When we get close, we choose to use smaller step size to avoid oscillation around the solution. In our context, we choose a small and constant step size as the range of CCHI is not large, we can approach it fast and accurately with small step size.

4.3 Distributed consensus for estimating traffic density

We need to estimate current traffic density as one of the inputs to our algorithm. We run a distributed consensus algorithm to gather all estimation from each single node and finally, the average value is used. Using a distributed consensus to gather the traffic density information outperforms using the estimation from a single node as it minimizes the estimation error and thus majority of nodes will benefit from the algorithm. It works as follows. Each distributed device has to estimate the density and transmit it to its connected Road Side Unit (RSU). Each RSU will calculate the mean traffic density and then deploy a distributed consensus algorithm [18] to achieve the consensus of the density. After achieving this consensus, they will use density as input to the proposed algorithm to produce an update interval. Finally, during next CCH interval, RSU will fill the update interval in a WAVE Short Message (WSM) and flood it to vehicles. As we include the new interval information in the routine WSM, it does not introduce extra message overhead in the protocol.

4.4 Summary

Supporting multi-channel operations in a single DSRC radio will cause significant performance loss as the bandwidth is split equally to the CCH and SCH. To tackle this problem, we propose a multi-channel coordination algorithm based on the analytical model in chapter 3. This algorithm utilizes the idea of iterative control. We update the channel interval length directly based on current packet loss ratio. It converges fast to the optimal interval length and can well balance the reliability of safety messages and throughput of non-safety messages comparing to current scheme in the Standard.

Chapter 5

Model Validation and Performance Analysis

In this Chapter, we conduct simulations to validate the proposed analytical model and then evaluate the performance of the multi-channel coordination algorithm. We consider a free-way system where all vehicles are distributed according to a Poisson process. Simulations are conducted on a a 2000 m highway segment. Each vehicle is equipped with an on-board DSRC wireless device. Road Side Units (RSUs) are also present to provide non-safety services. Hence, both V2V and V2I communications are included in the simulation. Moreover, we leverage the IEEE 802.11p as the MAC protocol and the two-ray ground reflection model as the physical propagation model. Due to finite transmission range and carrier-sense range used in our system, hidden terminals, concurrent collisions and synchronized collisions are naturally reflected in the simulations.

We begin by introducing the simulations platform in Section 5.1, and describe the parameters we use in the simulation in Section 5.2. In Section 5.3, we validate our model and in Section 5.4, we present evaluation results from the simulation.

5.1 Simulation Platform

We use the Network Simulator 2 (ns-2) [39] as the main tool to simulate DSRC and the proposed algorithm. NS2 is a famous discrete event network simulator, which is publicly available under the GNU GPLv2 licence for research and development. It uses Tcl instead of MIT's Object Tcl (Otcl) as simulation scripts. The core of the program is implemented in C++. The CMU IEEE 802.11 MAC and PHY models are used as the MAC layer and Physical layer of our system, respectively. We implement DSRC multi-channel based on the toolkit released by Ghandour [3]. CCH and SCHs are interleaving as we declare one's medium to be busy when the other is operating. The system supports both broadcasting and unicasting. In addition, we use Matlab to process simulation traces.

5.2 Simulation Setup

We consider a typical highway scenario where the distribution of vehicles follows a Poisson distribution. Each of the nodes has the same transmission range. Especially, we choose the node in the middle of the lane as the tagged node as it does not suffer any edge effect. Each channel has a 10M Hz bandwidth. The packet arrival processes of both CCH and SCHs satisfy the Poisson distribution. The packet generating rate of CCH is 10 Hz and for SCHs, the rate is 100 Hz - 500 Hz as we consider that there are more packets from non-safety applications. The main parameters of 802.11p used in the system are summarized in Table 5.1. We adopt standard two-ray ground reflection model as the physical model in the simulation. This model has been thoroughly measured and characterized in the mobile V2V environment. The model considers both the direct path and a ground reflection path.

Table 5.1 Simulation Configuration

Parameter	Value
Density(β)	0.01-0.1 vhls/m
Transmission range(R)	450m,378m,180m,102m
Carrier Sense Range(L_{cs})	750m
Interference Range(L_{int})	600m
Frequency	5.9GH
PHY header(PHY_H)	48bits
MAC header(MAC_H)	28 bytes
SIFS	32 μs
DIFS	64 μs
DATA rate(R_d)	3Mbps, 6Mbps, 12Mbps, 24Mbps
Slot time(σ)	13μs
Contention Window(W_0)	15

The received power at distance d is predicted by

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{5.1}$$

where h_t and h_r are the heights of the transmit and receive antennas respectively.

5.3 Model Validation

In this section, we validate PLR and throughput models by comparing their theoretical values with simulation results. Figure 5.1 shows the Packet Loss Ratio with varying traffic density. In this scenario, we separate the PLR caused by interference and PLR caused by fading. In Figure 5.1, the PLR only suffers from interference, which is what our model describes. When the traffic density increases, the PDR has a significant drop. The results of our model coincide with the simulation counterparts, which tell that our theoretical analysis well capture features of DSRC systems. The 5% gap between the analytical and simulation results is due to the limited precision of numerical differentiation and limited road range in the simulations.

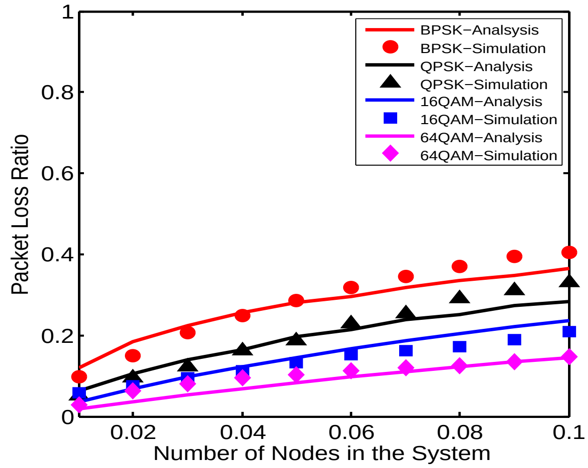


Fig. 5.1 PLR of CCH channel with BPSK and QPSK modulation

To validate the system throughput model, we perform simulations with varying packet sizes and the modulation technique is BPSK. We do not consider other modulations in this case as fading has a significant impact on them. And we can not separate throughput impacted by interference standalone and throughput impacted by fading standalone. As BPSK is resilient to fading and we place all nodes at the same place on the lane, the throughput in Figure 5.2 is only impacted by interference, which is also the focus of our throughput model for MAC layer. We observe the throughput in SCHs for different packet sizes in Figure 5.2. The throughput has a negative relation with the traffic density as interference will be stronger when more nodes are present. The simulation results also match well with the proposed model. When setting the packet size to 200 bytes, the throughput is slightly smaller. This is because the network condition is not saturated.

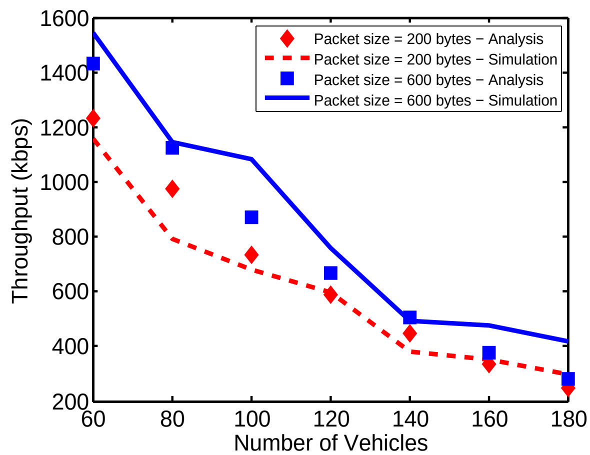


Fig. 5.2 Throughput in SCHs for different packet sizes

5.4 Performance Evaluation

We test the proposed algorithm with step sizes λ and ζ equal to 0.02 and 0.01 respectively. We take the BPSK communication range as the reference range when calculating PLR.

5.4.1 Impacts of Main Parameters on the Performance

Synchronized Collision Problem

We demonstrate the synchronized collision in this experiment. We focus on CCH and divide CCH interval into five time slices. The first time slice is 0 ms-5 ms, which suffers synchronized collision most. The second slice is 5 ms-10 ms. For other slices, the length is 10 ms. Then we record number of packets transmitted during each time slice. Figure 5.3 shows the percentage of total packets transmitted during each time slice. As we observe, the number of packets transmitted in the first slice is far more than number of packets transmitted in other slices. The reason is that each time, packets which have been generated but not able to be transmitted in time will be put in the queue. In the next synchronization

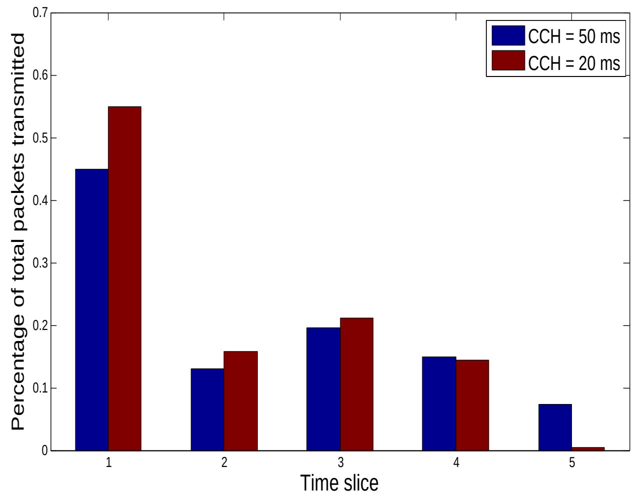


Fig. 5.3 Percentage of packets sent during each time slice (Traffic density = 0.4 vhls/m)

interval, these packets are ready to be transmitted right away. Almost each node has a packet ready to be transmitted at the same time (the start of the interval). Thus most packets are sent in the first time slice. This is also the reason for synchronized collision as they may very likely to choose the same time slot to start the backoff process. Thus PLR of the system is thus degraded.

Impact of packet size on PLR

The relationship between the overall PLR and packet size with QPSK modulation is shown in Figure 5.4. PLR increases with packet size. This is because the larger the packets, the longer it takes to be transmitted, thus leading to longer vulnerable period.

Impact of traffic density and modulation techniques on PLR

Figure 5.5 shows the the impact of modulation techniques and traffic density on PLR. It is shown that 16QAM and 64 QAM always suffer high packet loss than BPSK and QPSK.

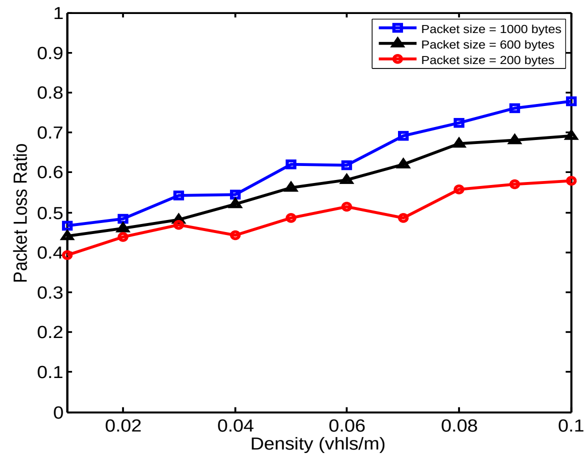
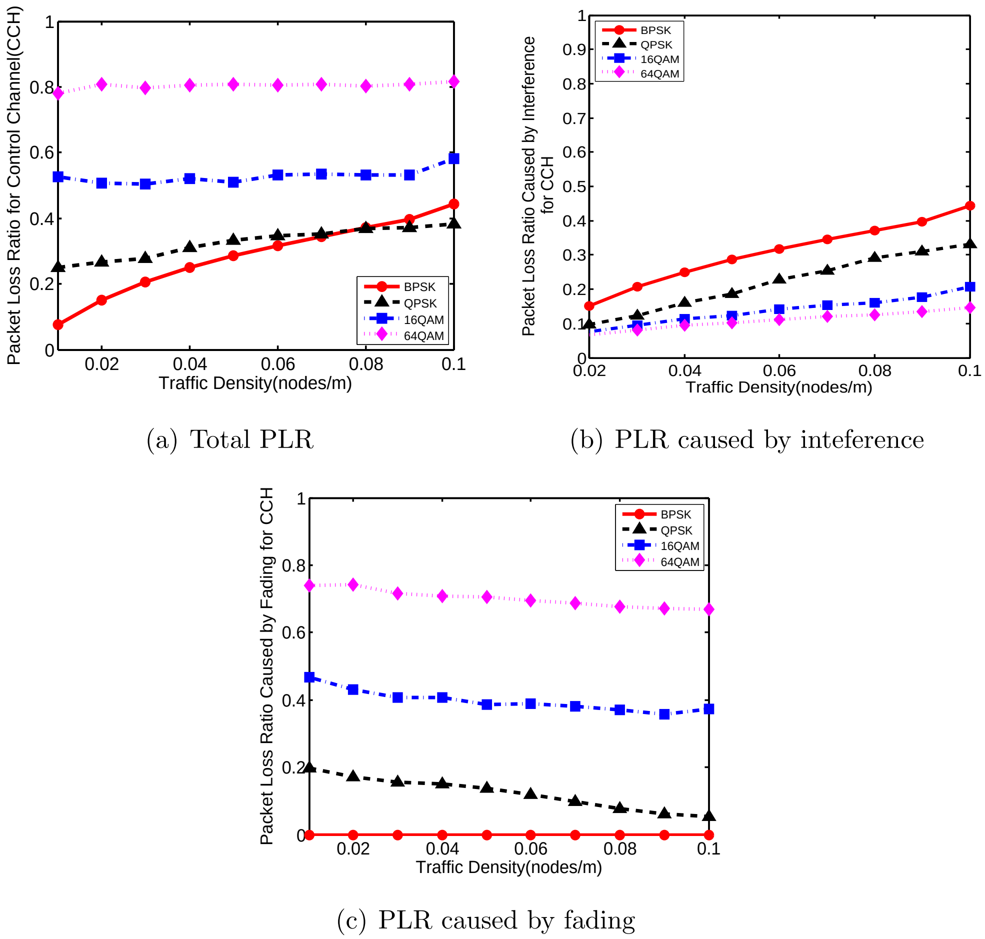


Fig. 5.4 Impact of packet size and traffic density on Packet Loss Ratio in SCHs

Moreover, BPSK outperforms other modulation techniques in low density and QPSK is the best in high density. We further analyse the PLR by showing the portion caused by interference (PLR_{int}) and the portion caused by physical fading (PLR_{fading}). Figure 5.5(b) shows PLR_{int} increases with traffic density and data rate. This is due to the fact that higher data rate reduces the vulnerable period, and thus suffers less hidden terminal impact. Nevertheless, Figure 5.5(c) shows that high level modulations incurs high PLR fading as they have comparatively short transmission range. Any receiver beyond that range will not receive packets. As PLR_{int} and PLR_{fading} have inverse trend when density increases, there is a cross point in total PLR for BPSK and QPSK. As in low density, the interference is not that high, and BPSK is more resilient to fading, so BPSK has a lower total PLR. However, in high density, interference is more significant, which makes QPSK outperforms BPSK.

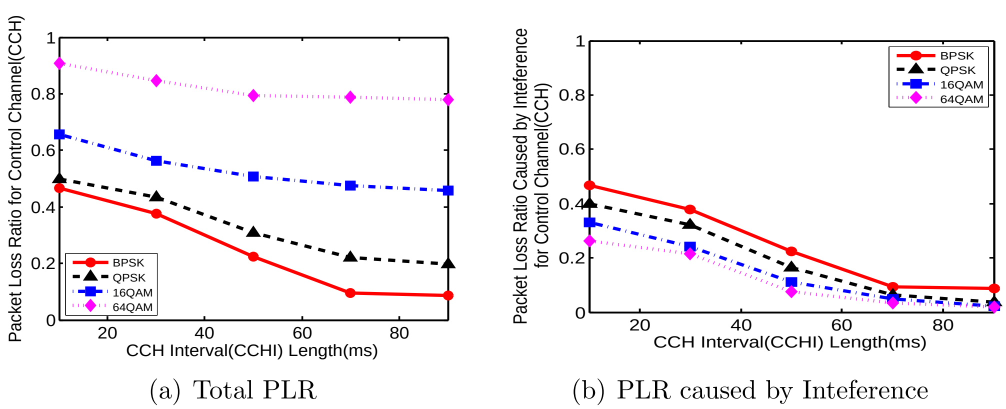


(a) Total PLR

(b) PLR caused by inteference

(c) PLR caused by fading

Fig. 5.5 Impact of traffic density on DSRC reliability



(a) Total PLR

(b) PLR caused by Inteference

Fig. 5.6 Impact of CCH interval on DSRC reliability

Impact of CCH interval on saturated throughput

Figure 5.6 and Figure 5.7 show the impact of CCH interval on PLR and saturated throughput of the tagged node. From the figure, we observe that larger CCHI can reduce PLR, thus increasing reliability. While for SCHs, if the CCHI increases, SCHI would correspondingly decrease and vice versa. This results in a decrease in the saturated throughput in SCHs.

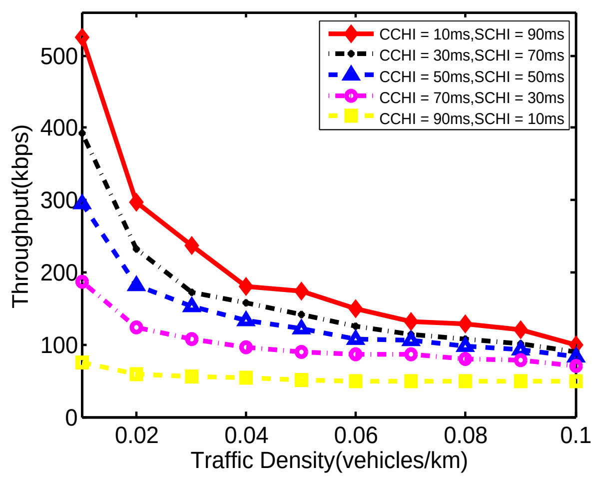


Fig. 5.7 Impact of traffic density and CCH interval (CCHI) on Saturated Throughput in SCHs

5.4.2 Performance of the proposed algorithm

We compare the performance of our algorithm with that of IEEE 1609.4 alternating access. We set the desired PLR to 0.2, a reasonably high reliability in automotive industry [13]. From Figure 5.8, we observe that optimal CCH interval increases with traffic density. As mentioned before, high traffic density leads to poor reliability as more inter-vehicle interference appears. We should enlarge CCH interval to provide more reliability. To this purpose, the proposed algorithm responds quickly to the PLR change and accurately adjusts CCH interval. In terms of accuracy, we mean that the algorithm constrains the

PLR under the pre-defined reliability requirement, and then provisions all the bandwidth to SCHs, thus increasing SCH throughput. Figure 5.9 presents the PLR varies with traffic density under the optimal interval. The proposed algorithm under all densities keeps the PLR under the desired reliability. Our algorithm significantly outperforms the alternating

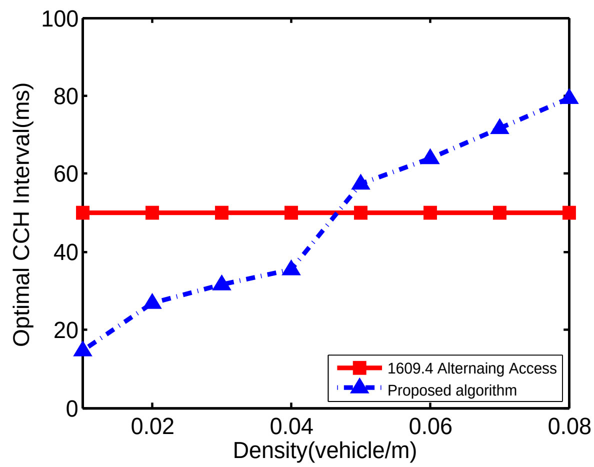


Fig. 5.8 Optimal CCH interval length

access, which has around 40% packet loss when the density is around 0.08 vehicles/m. Figure 5.10 shows the throughput in SCHs of the tagged node varies with traffic density. When the traffic density is low (i.e. under 0.05 vehicle/m) the proposed algorithm leads to the highest throughput possible in this scenario as the smallest possible CCH interval is used and more operating interval is reserved for SCH. When the density is high, CCH interval is enlarged to provide more reliability. Additionally, we find that in low density cases, the proposed algorithm achieves significantly higher SCH throughput than the other while it only has minor throughput difference under high density. It is believed that our algorithm is lightweight while effective. It is flexible to add different messages in our algorithm, e.g. WSA and RFS. In some research, WSA and RFS are sent in every duty cycle. However, some work just use WSA and RFS as handover message. Our algorithm

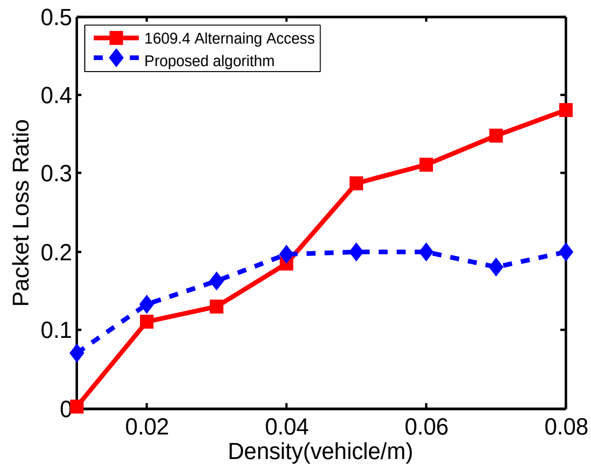


Fig. 5.9 Packet Loss Ratio in CCH under the desired interval

works in both scenarios as we directly control the reliability which is more flexible in design and implementation comparing to other algorithms.

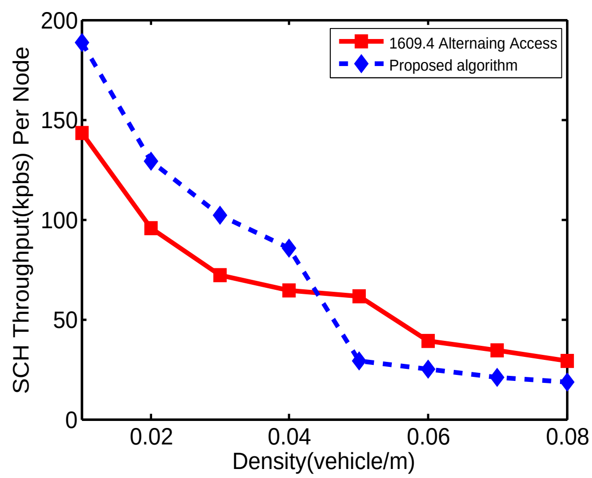


Fig. 5.10 Throughput in SCHs under the desired interval

5.5 Summary

In this chapter, we first introduce our simulation platform and then describe the set-up of our system. The analytical model is validated by comparing its theoretical values and the simulation results. Moreover, results also show that our algorithm relieves synchronized collision and is effective to guarantee safety message reliability as well as achieving high throughput in low density scenario.

Chapter 6

Conclusions and Future Directions

This thesis addresses a dominating problem for DSRC commercialization that how much DSRC can be used to support non-safety services while providing sufficient reliability for safety applications. Though the primary purpose of DSRC is to provide reliable communication for safety related applications, non-safety services also play a major role in DSRC's deployment as it makes DSRC more cost-effective. Control channel and service channels operate on a TDMA basis. Therefore, how to divide the time interval to achieve the requirements in both channels is a critical issue. To tackle this challenge, we first build two analytical models for CCH broadcasting and SCH unicasting based on Markov Chain (MC), where multi-channel operation is included and synchronized collision is analysed. In addition, we propose a multi-channel coordination algorithm to adaptively choose an optimal CCH interval based on current Packet Loss Ratio (PLR). A PLR threshold is predefined. If current PLR exceeds the threshold, the CCH interval will be updated to a larger value to guarantee the reliability. Otherwise, it will be reduced to provide more bandwidth for SCHs. Our approach converges rapidly to the optimal interval. Moreover, if the traffic density remains stable, the algorithm quickly converges to the optimal channel interval.

We hope to shed insights on how to design an effective channel access approach to increase SCH throughput, and thus, expediting DSRC's deployment.

6.1 Future Directions

In addition to simulation work in NS2, we also plan to test this method with real DSRC radios. Moreover, data from real-world experiments would help build more accurate analytical model, e.g. we can use machine learning methods to find a better propagation model. It is also interesting if we could design a distributed multi-channel coordination algorithm that is independent of RSUs while having channel synchronization. Another possible direction is to study DSRC vehicle-to-motorcycle (V2M) and vehicle-to-pedestrian (V2P) communication. Figure 6.1 is a demo by Honda to demonstrate their new DSRC

Fig. 6.1 DSRC on-board unit can also communicate with smart-phone equipped pedestrians [32]

V2P systems. These new contexts bring out new challenging problems. As the density of people, especially in downtown area is larger than that of vehicles, this will challenge traditional congestion control techniques. Another challenge is how cellphone can support

DSRC without significant battery cost. Figure 6.2 is a primary investigation of this problem by Qualcomm. They have integrated DSRC hardware support to their new generation phones. To save battery, a possible approach would be to design an intelligent mode switch algorithm that enables cellphone to be aware of when to wake up to receive safety messages.

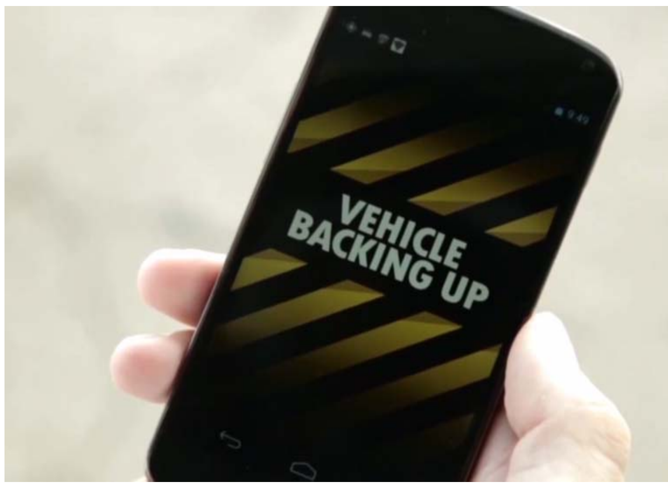


Fig. 6.2 DSRC enabled smart-phone [32]

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