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A Clustering-based Multi-channel Vehicle-to-Vehicle (V2V) Communication System

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by

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Abstract

For any type of transportation system, traffic safety is a global concerned issue that attracts the most attentions. Within the U.S only, millions of crashes happen every year, leaving tons of deaths and tremendous economic losses. Therefore, considerable efforts from research institutes, governments, and industry have been undertaken to reduce or even eliminate traffic accidents.

Intelligent Transportation System (ITS) has been developed to enhance traffic safety by using Vehicle-to-Vehicle (V2V) or Vehicle-to-Roadside (V2R) communications. ITS allows a vehicles that equipped with wireless communication devices to exchange information with its neighbors or roadside data centers. That is to say, vehicles are no longer isolated, but can make up Vehicular Ad Hoc Networks (VANETs), a special form of Mobile Ad Hoc Networks (MANETs), which allow inter-vehicle communications. VANETs make “smart vehicle”, which is able to avoid traffic accident spontaneously,

become possible. However, numbers of challenges are faced by researchers to make the VANET efficient and feasible enough in the real-world circumstance. One of the primary challenges of current VANETs study is to achieve real-time information exchange among vehicles for enhancing traffic safety. To achieve this goal, information dissemination requires timely and lossless wireless medium access, which brings new difficulties to the design of MAC (Medium Access Control) protocols.

In this thesis, we propose a clustering-based multi-channel V2V communication system to provide traffic accident avoidance mechanism. In the proposed system, vehicles are self-organized into different clusters, and the traditional single common medium in a MANET has been divided into multiple control channels and a single data channel. Since a GPS (Global Positioning System) is easy to equip into a vehicle and provide synchronized standard time, infrastructure-based TDMA/CDMA (Time Division Multiple Access/Code Division Multiple Access) technique is adopted for intra-cluster and inter-cluster data communications. For the control channels, a contention-based IEEE 802.11 MAC protocol is utilized to coordinate the medium access in a fully distributed manner. A novel TDMA/CDMA hybrid MAC protocol is designed for the data channel to achieve low transmission delay.

Another contribution of this research work is the systematic study of the highway traffic model. To the best of our knowledge, most V2V communication systems proposed so far were built on an extremely simple highway model, which means not feasible in the real world. However, the highway traffic model designed in this research work is based on the real-world environment, whose vehicles are allowed to performance real driving behaviors. This advanced highway traffic model makes our proposed V2V communication system can be used in any type of road condition.

A sophisticated event-driven simulator has been developed by C++ language. The system is evaluated by extensive simulations. The simulation results show that the proposed system can provide better performance for safety supporting than most existing schemes.

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List of Abbreviations

MAC	Medium access control
IEEE	Institute of electrical and electronics engineers
DCF	Distributed coordinate function
PCF	Point coordinates function
WLAN	Wireless local area network
MANET	Mobile ad hoc network
VANET	Vehicular ad hoc network
CSMA/CA	Carrier sense multiple access with collision avoidance
CSMA	Carrier sense multiple access
RTS	Ready to send
CTS	Clear to send
ACK	Acknowledgement
DIFS	Distributed inter-frame space
SIFS	Short inter-frame space

QoS	Quality of service
IVC	Inter-vehicle communication
V2V	Vehicle-to-vehicle
V2R	Vehicle-to-roadside
CH	Cluster head
CM	Cluster member
FN	Free node
ITS	Intelligent transportation system
DSRC	Dedicated short range communication
BTS	Bureau of transportation statistics
TDMA	Time division multiple access
CDMA	Code division multiple access
FDMA	Frequency division multiple access
GPS	Global positioning system
DMAC	Directional medium access control
ASDM	Adaptive space division multiplexing
SDMA	Space Division Multiple Access
VAAM	Vehicle accident avoidance mechanism
MCS/CDMA	Multi-code sense code division multiple access

Chapter 1

Introduction

1.1 Motivation and Background Introduction

1.1.1 Motivation

The number of personal vehicles is soaring in recent years, especially in developing countries. Traffic safety is no longer a difficult problem confronts developed countries, but a global concerned issue due to huge amounts of traffic accidents causing injuries and deaths every year. For example, the USA Bureau of Transportation Statistics (BTS) reported that, in 2006 within USA only, there were more than 7.1 million reported vehicles crashes, which leading to 1.74 million deaths and more than \$450 billion property losses [1]. With this immense number of crashes, leaving millions of deaths, and tremendous economic losses, considerable efforts from research institutes, industry, and governments are undertaking to reduce or even eliminate traffic

accidents.

Supposing a moving vehicle has enough information, such as its neighboring cars' real-time moving speeds and relative distances etc., this vehicle may be able to avoid the accidents by automatically employing a pre-designed traffic accident avoidance system. How to obtain neighboring cars' information becomes a key issue. Therefore, designing an efficient Vehicle-to-Vehicle (V2V) communication system to enhance traffic safety is very important.

1.1.2 Vehicle-to-Vehicle (V2V) Communication Systems

Intelligent Transportation System (ITS) [2] is being developed for enhancing traffic safety using V2V (Vehicle-to-Vehicle) or V2R (Vehicle-to-Roadside) communication systems [3]. The ultimate goal of ITS is to provide a feasible vehicle-based infrastructure that not only efficiently reduce or even eliminate the traffic accident, but also offer a high-speed information sharing wireless platform among vehicles. Vehicles equipped with wireless communication devices are no longer isolated, and can make up Vehicular Ad Hoc Networks (VANETs) [4], a special form of Mobile Ad Hoc Networks (MANETs), to make V2V communications possible. VANETs enable vehicles to exchange information, and also allow vehicle-based large-scale sensing, decisions, and control actions [5] [6].

The first milestone of standardization process of VANETs was the allocation of 75 MHz in the 5.9 GHz band for Dedicated Short-Range Communication (DSRC) [7], which supports seven separate channels, may also enable the future delivery of rich multimedia contents to vehicles at short-to-medium range via either V2V or V2R links in VANETs.

VANETs make the “smart vehicle”, which is able to avoid traffic accident spontaneously, become possible. It extends the horizon of drivers and automated system in the inter-vehicle communication not only helps the drivers acquire real-time traffic information and react quickly, but facilitates smooth driving according to varying transportation conditions [8][9].

While there has been a large body in the literature studying both V2V [10]-[14] and V2R [15] [16] networks, there are several advantages of using V2V-based VANETs as compared with V2R-based VANETs. First, V2V-based VANETs are more flexible and independent of the roadside conditions, which is particularly attractive for most developing countries or remote rural areas where roadside infrastructures are not necessarily available/furnished. Second, V2V-based VANETs are less expensive than the V2R ones since they do not need expensive roadside stations. Third, V2V-based VANET can avoid the fast fading, short connectivity time, high frequent handoffs, etc., that are caused by the high relative-speed difference between the fast-moving vehicles and the stationary base stations. Finally, V2V-based VANET much better fits

vehicle-related applications, which only needs to exchange data/information among neighboring vehicles and within their nearby areas. Therefore, there is no doubt that VANET is a fundamental component of ITS, and V2V-based VANET is believed to be the most feasible architecture for inter-vehicle communication in a fully distributed circumstance.

1.1.3 Challenges in Vehicle-to-Vehicle Communication Systems

It is no doubt that V2V-based VANETs will have a bright future. However, there are still many tough challenges confront researchers. Even though VANET is a special form of MANETs, it has some inimitable characters that make protocols that implemented efficiently in MANETs cannot be directly transplant to VANET environment. Driving behaviors, fast moving speeds of vehicles, mobility constraints, unpredictable turns etc. [17] contribute the uniqueness of VANETs. As a result, a VANET suffers a rapid network topology change [18], small effective network diameter [19], and unlimited redundancy [20], all of which bring new challenges of designing efficient protocols in VANETs.

One of the most important applications of VANETs is the traffic safety supporting, which requires low-delay medium access, fast packet transmission and low rate of packet losses. In such a case, Medium Access Control (MAC) becomes the most critical issue in the communication

processes between vehicles. However, designing MAC protocols for safety message dissemination in VANETs is a challenging topic. The reason is that MAC in a typical V2V-based VANET needs to be fully distributed due to the constantly moving and speed changing in the networks.

Current MAC protocols in VANETs can be categorized into two different types: contention-based and contention-free. The contention-based approaches can be operated in fully distributed environment, which means no central infrastructure is needed to coordinate the inter-vehicle communications. What is more, the contention-based MAC protocols have the advantage of not being sensitive to underlying mobility and topology changes. Therefore, unlike the contention-free protocols, the fast movements of vehicles in VANETs do not impose any reconfiguration overhead due to the network topology changes. However, the disadvantages of contention-based MAC protocols are also obvious. Packets have to experience unbounded delay in media access due to deferrals and backoffs. Unpredictable medium access delay is however intolerable for those time-sensitive applications, such as traffic safety message transmission, who asks for low end-to-end transmission delay and real-time network topology information. Apart from the delay, packet loss is also a big problem for contention-based MAC protocols. The packet loss rate may soar when the density of vehicles is increasing, due to the heavy traffic load causing frequent collisions.

Compare to contention-based approaches, contention-free MAC protocols also have their advantages and shortcomings. The most significant advantage of contention-free MAC protocols is that the access delay is bounded and limited to an acceptable range, thanks to the coordinate of the existing central stations. What is more, the possibility of collision is very low in contention-free MAC protocol. No matter TDMA, CDMA, token rings etc. is chosen as the contention-free approach, every vehicle will have its own transmission priority to guarantee that the packet transmission process is interference free. Yet, the critical disadvantages of contention-free MAC protocols make them really hard to be deployed in real VANETs. Contention-free approaches are extremely sensitive to the network topology changes. The process of reschedule current transmission layouts will bring large overhead that waste the precious bandwidth. After that, all of current contention-free MAC protocols require synchronization in the networks. To the best of our knowledge, how to achieve synchronization in a VANETs using only one wireless channel is still an open challenge to be resolved. Lots of efforts have been made to implement contention-free MAC protocols into VANETs. [21]- [23] propose similar TDMA MAC mechanisms, in which TDMA slots are self-selected by the nodes in a distributed manner. Although the data latency is bounded, the slot allocation process is still contention-based, which leads to collision and packet losses. That is to say, the slot re-distribution due

to topology change may often occur a huge access delay before the data can begin to exchange. A token ring MAC protocol is proposed in [24]. Due to the principle of token ring based protocol, the maximum transmission delay is always bounded by the round-trip token time. However, the delay may increase dramatically due to the high vehicle density. This drawback can be solved by introducing multiple rings, but then the fast topology changing will cause frequent ring management reconfiguration. Long end-to-end delay caused by large reconfiguration overheads can be expected. MCS/CDMA (Multi-code sense code division multiple access) [25] is another contention-free MAC protocol utilizing CDMA technique. In the proposed protocol, each vehicle is assumed to have parallel receiver matched filters corresponding to all the usable CDMA codes. If the process of searching for free code is done sequentially, it will take a long time to finish when the number of involved vehicle is large. When the network topology is changing, the code distribution will add extra overheads and considerable transmission latency. Also, contention for free CDMA code will happen if there are more vehicles than available codes, which may lead to large delay in medium access.

Although IEEE 802.11a [26] is the recommended MAC protocol for VANETs [27], it suffers from a large number of packet losses due to collisions and access delays, which are the common problems of contention-based MAC protocols. A lot of schemes have been proposed to improve the performance of

MAC protocol in VANETs [28]-[30]. In [28], the authors propose a vehicular self-organizing MAC protocol which use TDMA scheme as the MAC protocol. The purpose of [28] is to achieve the reconfiguration of TDMA slots without central controls and provide dependable data transmission in V2V communication. However, how to synchronize TDMA time slots among different vehicles by using only one wireless channel is not clearly presented. A cross-layered MAC protocol and clustering scheme for multi-hop broadcast of emergency message in VANETs are proposed in [29]. Clustering scheme is designed for a virtual backbone network of VANETs. A Dynamic Backbone-Assisted MAC (DBA-MAC) protocol and multi-hop forwarding techniques are used to improve the throughput of the virtual backbone network. However, the creation of the backbone is a pre-activated manner, which brings large overheads that waste precious channel bandwidth. In [30], a clustering-based MAC protocol is proposed for supporting QoS (Quality of Service) in VANETs. TDMA scheme is used inside each cluster for dependable packets exchange. The IEEE 802.11 MAC protocol is adopted for cluster heads' communication to coordinate inter-cluster information. Ignored the hidden/exposed node problem is the major drawback of this research work.

1.2 Contributions

Our accomplishments, which are dedicated throughout this thesis, can be roughly listed as follows:

- Model and simulate a sophisticated highway traffic model, on which our proposed a V2V communication system is based. Rather than only allow vehicles move at a constant and unchanged manner on the highway in most of other researches, the highway traffic model studied in this research work set the vehicles free to perform real driving behaviors, such as acceleration, deceleration, lane change, detouring, and merging. The well-considered design and implementation of our traffic model not only makes our research on vehicular ad hoc networks and simulation results more convincing and meaningful, but allows the proposed V2V communication system can be implemented in any kind of road condition.
- Study and propose a cluster-self-organizing algorithm to manage and coordinate the formation and reorganization of the vehicle clusters. A novel algorithm is been developed to resolve the problem that how to organize vehicles into clusters in the preliminary stage (no cluster exists in this stage), which is a long ignored touch question in other VANETs studies.

- Research and propose a TDMA/CDMA MAC protocol to coordinate the intra- and inter-cluster communications. This MAC protocol enables vehicles to access the wireless medium in bounded delay and extremely low packets loss rate during the communications. What is more, the hidden and exposed terminal problems have been successfully addressed by the proposed MAC protocol, which improves the throughput of VANETs significantly.
- A Vehicle Accident Avoidance Mechanism (VAAM) has been researched. With the help of our proposed V2V communication system, VAAM will be automatically utilized by vehicles to analyze the real-time moving statuses, and raise an alarm if there is any potential danger. Thus, the accident can be avoided efficiently.
- Extensive simulations have been implemented and analyzed. The comprehensive simulation results are discussed. The performance of the proposed V2V communication system is compared with other research works that use IEEE 802.11a or similar protocols as their MAC protocols to verify the advantages of our research.

1.3 Organization of the Thesis

The rest of this thesis is organized as follows. In Chapter 2, we introduce

the techniques that have been adopted in current VANETs to help readers have basic knowledge. In Chapter 3, the proposed highway traffic model and the V2V communication system will be presented in detail. Chapter 4 evaluates the proposed system performance by using extensive simulations. The results are studied and analyzed carefully. Finally, we conclude this thesis and give an overview of future research direction in Chapter 5.

1.4 Summary

In this chapter, our motivation of this research work was presented. We introduced the concepts of VAENTs and V2V communication systems. The challenges issues that confront current researches have been discussed. We summarized our contributions that elaborated throughout this thesis and gave an overview of how this thesis is organized.

Chapter 2

Preliminaries

2.1 Introduction

In transportation system, a vehicle may be able to avoid traffic accident if the driver can see further down the road to know if there is collision happened, or if the vehicle is approaching a traffic jam. This can be achieved by letting vehicles to communication with their neighbors or with the roadside data centers. Supposing a vehicle has real-time information about its neighbors' positions, moving speeds and moving directions, the road and traffic safety would be improved.

Vehicles equipped with wireless communication devices make it possible to build a multi-hop wireless network among them. Vehicles on the road are no longer isolated, but could form a VANET, which is a special MANET. Vehicle-moving related information could pass along VANETs, and enable drivers be aware of the emergency situations occurred on the road, such as

sudden braking of a preceding vehicle, or the presence of an obstacle in the roadway. VANETs' emergence not only helps vehicles to reduce or even avoid potential accidents, but also enables them to utilize the roadways efficiently.

2.2 Radio Technologies used in Vehicle-to-Vehicle (V2V) Communication

In this section, we will introduce different radio frequency technologies that can be used in V2V communication.

Both infrared and radio wave can be chosen as the possible candidates for the inter-vehicle communication. Numbers of radio technologies can be classified into two categories, directional communication and broadcast communication. For example, infrared and millimeter waves are known as directional communication technique, while VHF and microwaves are a type of broadcast communication. According to [31], microwaves are the radio technology that been used most often in V2V communication. For instance, 75 MHz is allocated in the 5.9 GHz band for Dedicated Short Range Communication (DSRC). Bluetooth, which operated in the 2.4 GHz band, is another option for the communication between two vehicles. However, the relatively short reliable transmission range limits its deployment in VANETs. Another disadvantage of Bluetooth is that it may take up to 3 seconds to

establish the communication, which is not suitable for fast topology change just like VANETs. In addition, since the Bluetooth strictly requires a master and slave setup, the master may be communicating with one slave, therefore, communication requests from other nodes may easily slow down the communication rate or even cause a collision.

Ultra-Wideband (UWB) is a new radio frequency technique known as an alternative to Bluetooth. UWB's wideband nature of the signal makes it been widely used in radar and back-bone applications, which require large bandwidth and fast transmission. The Federal Communication Commission (FCC) refers to UWB technology as having high values of fractional bandwidth (>0.25) [32]. The main advantages of UWB technology are its high data rate, low cost, and immunity to interference [32]. However, it does have some disadvantages, such as it could possibly interfere with other existing radio service, like GPS and satellite radios. Gaussian pulse is chosen as the major waveform in UWB. It benefits a lower Bit Error Rate (BER) and not very sensitive to multipath or jitter effects. Thus, Gaussian pulses waveform is thought to be superior to monocycle pulses. The fact that UWB could potentially interfere with communication sources is a technical problem that must be solved before it could be used in V2V communication systems. Also, there is a concern that UWB's radio coverage could extend to uninvolved vehicles, which could generate false or irrelevant information [32].

2.3 Medium Access Control (MAC) in V2V Communication

VANET is a special manner of MANET. It has been proved that ad hoc network architecture is more suitable for fully distributed V2V communication systems than centralized networks. The main drawback of a centralized architecture is that it is very difficult to elect central stations among fast-moving vehicles. Even if the election is possible, it will bring huge overheads and waste precious bandwidth. Also, it is very inefficient of centralized architecture since information has to be sent to central station from one vehicle at first then delivered to another vehicle. Wireless communication among moving vehicles can be achieved by using current IEEE 802.11 compliant wireless devices. The IEEE 802.11a-based devices maximize the transmission data rates up to 54 Mbps [33]. Compared to traditional MANETs, challenges are greater when deploying ad hoc networks in vehicular traffic scenario. These are caused by fast changing network topology, unpredictable driving behaviors, and different driving environments.

2.3.1 Directional MAC (DMAC) Protocol

MAC protocol plays a very important role in V2V communication. A robust MAC scheme is needed for increasing the throughput of a VANET and making

the vehicles to share the wireless channel more efficiently. Several MAC protocols based on IEEE 802.11 standard have been introduced into V2V communication from MANETs. Most of these protocols require using omni-directional antennas as their communication interface. However, directional antennas attract more and more attentions in recent years. The main advantage of directional antennas is that they can improve the performance of wireless networks significantly by increasing the spatial reuse of channels. In order to benefit from the use of directional antenna, MAC protocols that can fully support the physical layer's directional transmission capabilities are needed badly. The Directional MAC (DMAC) protocol is one of the protocols that can be used to efficiently coordinate directional transmissions [34]. DMAC can help to avoid the hidden and exposed problems by making a vehicle to tell its neighbors to postpone their transmissions if it is going to harm the pending transmissions. This mechanism is also a basic but efficient way to obtain neighbors' moving information, such as speeds, locations etc., which can be used in the directional transmission.

When a vehicle has data to transmit, a Request-to-Send (RTS) packet will be sent out directionally in a circular way. All of the directional antennas will be scanned until the area round the source node is found. The complete hand-shaking procedure CRTS (circular RTS) is composed of RTS-CTS-DATA-ACK. (CTS: Clear-To-Send, DATA: data, ACK:

Acknowledgement). Neighbors will stop their transmission only when they find themselves are towards the same direction as the sender's. Vehicles in the other spatial of the channel could continue sending their packets without any interferences or collisions.

Vehicles listen to the wireless channel omni-directionally when they are idle and have no data to send. However, a vehicle will change to use selection diversity the moment it received the CTRS signal. Directional CTS messages will then be sent by the vehicle via that antenna. The source vehicle begins transmitting its data upon receiving the CTS messages. Obviously, DMAC allows vehicles to communicate with each other simultaneously without knowing each other's exact locations.

DMAC is supposed to have better performance than others in vehicle-to-vehicle communication systems due to the increased spatial reuse. However, the mobility and unpredictable driving behaviors of vehicles make this may not occur. What is more, the DMAC's contention-based nature and hand-shaking procedure make DMA to have relatively long end-to-end delay, which cannot satisfy time-sensitive safety-related data's needs.

2.3.2 Adaptive Space Division Multiplexing (ASDM)

Security and Scalability issues are big concerns when the wireless communication occurs directly among vehicles. Take the Denial of Service

(DoS) threats for example, they may happen in the wireless medium and can disable communications in current network. Thus, spread spectrum techniques are proposed to offer protection for V2V communication to against jamming attacks. As the price, more bandwidth is required when the spread spectrum techniques are implemented, which also needs the protocols to have the ability to scale well when the available bandwidth shrinks. In addition, considering the uniqueness of VANETs, the protocols should be capable of scaling to a large network size with high density o vehicles, and the ability to quickly adapt to a fast changing topology is also demanded.

Adaptive Space Division Multiplexing (ASDM) [35], a new link layer protocol, has been proposed to address both V2V communication and security issues in VANETs. In ASDM, roadway is divided into cells, and each vehicle contains a mapping function that maps the cells to time slots. It distributes the time slots to vehicles that they can use based on the assignment rules. Actually, ASDM is an extension of Space Division Multiple Access (SDMA) which assigns the time slots to vehicle based on their locations on the road. ASDM also provide certain Quality of Service (QoS) by keeping an adequate following distance between vehicles. This distance is decided by the number of time slots a vehicle has. Thus, a vehicle's transmission frequency can be constant if it maintains a certain following distance. When the density of vehicle is increasing, for example when the traffic jam happens on a certain

roadway, the link layer has to deal with more vehicles within radio range than usual. However, since vehicles' speeds decrease, their periodic transmission rate may also decrease. Vehicles can maintain a reasonable QoS by shortening their following distance.

2.4 Clustering Technique in VANETs

Clustering is a technique that used to gather or group nodes in a network into different logically separated entities called clusters [36]. The formation of clusters in a network can simplify some important functions, such as node management, routing, medium access management, resource management and bandwidth allocation. There are some possible statuses of a node in a cluster, named cluster head, cluster member, gateway node, etc. The basic idea of clustering technique is to divide the whole network into different autonomous clusters. The cluster head in a cluster plays the roles as coordinator and backbone. It is in charge of all the communications inside a cluster, managing medium access and allocating the resource to cluster members. Cluster members do not have to worry about the communication between itself and others. The only thing they should do is to exchange information with its cluster head. Gateway nodes are responsible for the communication between the cluster it is currently in and the other clusters

outside.

How to choose a cluster head in a fully distributed ad hoc network is the key problem should be solved before implementing clustering. Several schemes have been proposed to address this challenge. There are lowest ID, highest degree, and node-weight heuristics [37]-[38]. Lowest ID algorithm is a widely used one. Every node in this algorithm will be assigned a unique ID to identify itself. After exchange ID with its neighbors, the node with lowest ID number will be chosen as the new cluster head.

However, VANETs pose new challenges in clustering schemes. These algorithms cannot be introduced into VANETs directly, for they aren't capable to the fast moving nodes, and frequent topology change. For example, vehicles change their speeds and lanes rapidly and frequently. The high-mobility nature of VANETs will bring huge computation overheads to vehicles when they use highest-degree algorithm to elect the cluster head. What is more, the cluster heads may change their relative locations on the highway frequently, which means the frequency of cluster head re-election is very high. Therefore, the re-organization of clusters will be executed frequently, which brings unpredictable size and stability of clusters. The lowest ID and node-weight heuristics algorithms can hardly be used in this scenario. On the other hand, vehicles' movements are limited by the roadway. Most of the vehicles have almost the same moving directions and speeds. Thus, the geographic

information and velocity of a vehicle may help the design of clustering schemes.

2.5 Multi-channel Technique in MAC Protocol Design of VANETs

It is known to all that the design of an efficient medium access scheme is more difficult in wireless networks than in wired scenario. This is due to the fact that the signal strength may fade while the distance is increasing in the wireless medium, which means the location factor has a great influence on the wireless medium access. Therefore, the traditional “listen-before-transmit” access schemes that work efficiently in wired networks do not operate well in the wireless environment. For example, the CSMA scheme has been proved to be an efficient MAC protocol in wired networks. However, hidden terminal problem may arise when introducing CSMA into wireless network, where two nodes could not hear each other send packet to a common receiver causing collision at that receiver.

In order to solve the hidden terminal problem, channel reservation technique has been implemented by random access schemes in wireless networks. The basic idea of the channel reservation technique is to exchange short RTS and CTS control packets between the sender and receiver before

data transmission [39]. This handshaking phase effectively performs a “virtual carrier sensing” at the receiver by letting the sender know the exact channel status at the receiver is idle or receiving other data. In addition, the channel will be temporarily reserved for the sender to transmit its data for other nodes who heard the CTS will defer their transmission for at least the duration of data transmission. This handshaking technique has been applied by IEEE Standard 802.11 for wireless LAN in asynchronous data transfer (called the distributed coordination function or DCF) [39]. In the standard, an ACK (acknowledgement) packet will be transmitted from the receiver to the send when the data transmission is finish. 802.11 DCF employs CSMA/CA (carrier sense multiple access with collision avoidance), which based on RTS-CTS-data-ACK 4-step handshaking, as its MAC protocol [40]. The idea behind CSMA/CA is that the senders do the channel-sensing before any data transmission. If the channel is sensed to be free for a DCF Inter-Frame Space (DIFS) time interval the transmission will be processed. If the medium is busy, the sender defers its transmission until the end of the current transmission and then it will wait an additional DIFS interval and generate a random backoff period before retrying. The random backoff period ensures the fairness among contending transmissions.

CSMA/CA on a single channel is proved to be inefficiently when the traffic loads are becoming heavy. Increasing traffic brings more collisions and longer

backoffs, both of which cause higher waste of precious wireless bandwidth. What is more, with the deployment of clustering technique and contention-free MAC protocols in wireless networks, the huge overheads also occupy large amount of bandwidth and significantly slow down the data transmission. Multi-channel technique attracts more and more attentions in recently years. The main idea of multi-channel technique is to divide a traditional common wireless medium into several sub-channels, which can be operated synchronously. The use of multiple channels may provide some throughput advantages in wireless networks by reducing collision and enabling more concurrent transmissions which means better bandwidth usage even with the same aggregate capacity. Multi-channel MAC protocols allow a couple of nodes to transmit their data on different channels concurrently without interfering one another. Nodes have data to send can now choose one of the channels with best performance to transmit by implementing an efficient channel selection algorithm.

Due to the advantages of multi-channel technique, a number of multi-channel MAC protocols have been proposed for wireless networks. These MAC protocols can be broadly classified into two categories based on the way how multi-channels are used [41]. In the first class, every node in the network is distributed a separate channel. The formation of channels is on the basis of individual CDMA codes. Transmission may be transmitter-oriented

(in which each node transmits using its own CDMA code) or receiver-oriented (in which all transmissions made to the same receiver using the same code) [41]. In the second class, every node does not own a dedicated channel any more. The common medium bandwidth is assumed to be divided into a number of sub-channels whose number is smaller than the number of nodes. All of these sub-channels can operate synchronously, and a node can transmit and receive on any channel.

Multi-channel technique surely brings some benefit to the design of MAC protocols in VANETs. However, there are still some challenges need to be settled before it can be widely deployed. For example, what is the MAC protocol for each channel, and how to coordinate the synchronous transmissions in different channels? One more channel requires one more set of transmitter and receiver. How many sub-channel should be divided to balance the network performance and equipment cost is still a problem.

2.6 Summary

In this chapter, we gave an overview of the techniques that utilized in VANETs and V2V communication systems. The advantages and disadvantages of different radio frequency bands that can be used to V2V communication systems are carefully studied and analyzed. Then, we focused

our discussion on the MAC protocols, which is believed to be one of the most important components of VANETs. At last, two cutting-edge techniques, clustering and multi-channel techniques were introduced to complete the discussion of the MAC protocols in VANETs.

Chapter 3

A Clustering-based Multi-channel Vehicle-to-Vehicle Communication System

3.1 Introduction

Undoubtedly, safety-supporting is one of the most important applications of VANETs. Most of the safety-related information, such as surrounding vehicles' locations and speeds, emergency reminding information etc., is time-sensitive and requires low transmission delay. How to achieve fast information exchange in VANETs is a big challenge faced by various researchers. If a moving vehicle has enough information, such as its neighboring cars' real-time moving speeds and relative locations etc., this vehicle may be able to avoid the accidents by automatically employing a pre-designed traffic accident avoidance system. How to obtain neighboring cars' information in a fast way becomes a key issue. Therefore, designing an efficient and short-delay V2V

communication system to enhance traffic safety is very important in VANETs.

ITS is being developed for enhancing traffic safety using V2V or V2R communication systems. VANET is one of the most essential components of ITS, and it is believed to be the most feasible architecture for V2V communication in a fully distributed circumstance. A VANET allows vehicles equipped with wireless communication devices to communicate with others in an ad hoc manner. However, a VANET suffers a rapid network topology change [4], and unlimited redundancy [41]. Such kinds of drawbacks increase the difficulty for VANETs to achieve real-time information exchange required by traffic accident avoidance systems and other time-sensitive applications. Therefore, many attempts are being made to improve the network performance of VANETs, which including designing fast routing algorithms and low-delay MAC protocols.

Although IEEE 802.11a is the recommended MAC protocol for VANETs, it suffers from a large number of packet losses and unbounded delay due to collisions and randomly backoffs, which are the common problems of contention-based MAC protocols. Even through IEEE 802.11a MAC protocol may work efficiently when the traffic density is sparse, its performance dose decrease dramatically when the traffic load becoming heavy. Obviously, high percentage of packet losses and unbounded end-to-end transmission delay makes contention-based MAC protocols hardly satisfy time-sensitive

applications' requirements. On another hand, the efforts of deploying contention-free MAC protocol in VANETs have never been stopped. The possibility of introducing contention-free MAC schemes, such as TDMA, CDMA, token-rings etc. to VANETs have been discussed by a lot of research works. The most significant advantage of contention-free MAC protocols is that the access delay is bounded and limited to an acceptable range, thanks to the help and coordinating of the existing central control infrastructures. What is more, the possibility of collision is very low in contention-free MAC protocol. No matter TDMA, CDMA, or token rings is chosen as the MAC protocol, every vehicle will be guaranteed that the packet transmission process is interference free. However, contention-free MAC protocols depend too much upon central control infrastructures and have extremely high requirement on the communication synchronization, both of which are not easy to achieve in VANETs. The election of central control infrastructures in a fully distributed ad hoc network like VANETs will bring huge overheads, which waste precious wireless bandwidth.

Since neither pure contention-based nor pure contention-free MAC protocols are perfect enough for V2V communication systems in VANETs, an idea of designing a hybrid MAC protocol that integrated the advantages of both contention-based and contention-free MAC protocols comes to our mind. In this chapter, we introduce a clustering-based multi-channel V2V

communication system to improve the safety of transportation. In our proposed system, vehicles are self-organized into different clusters, and the traditional single common medium in an ad hoc network has been divided into multiple control channels and a single data channel. All the control channels use IEEE 802.11 CSMA/CA protocol to coordinate the medium access, and a novel TDMA/CDMA MAC scheme is designed for the data channel to guarantee low end-to-end delay inside each cluster. The proposed system can achieve fast reactions to the emergency and warn drivers to take proper actions, which can effectively reduce the potential traffic accidents.

3.2 Highway Traffic Models

In the proposed V2V communication system, we consider a three-lane one way straight highway with length L . Entrances and exits of the highway are considered with the aim of making our highway model as close to real-world situations as possible. For simplicity, we assume that an entrance and an exit share a same road segment, which means entrance 1 and exit 1 refer to the same path. Entrances and exits locate on the highway's right side with one mile interval as in Fig.3.1. Even though there is no corner or turn in our proposed highway model, it does not prevent our V2V communication system from being used in any type of road condition.

It is assumed that each vehicle in the system is equipped with a GPS, which can provide a vehicle's real-time location information, moving direction and moving speed etc. We also assume that traffic stream enters the highway from the very beginning follows Poisson distribution with mean rate λ_1 . (Note: in this thesis, we use the terms “traffic stream”, “traffic flow” and “vehicle flow” alternatively, all of which have the same meaning.) On another hand, vehicle flow that enters the highway from each entrance also follows Poisson distribution, but with mean rate λ_2 which is set to smaller than λ_1 . The moving speeds of vehicles are randomly generated when the vehicles join the highway. Different speeds follow a truncated normal distribution in the range $[V_{min}, V_{max}]$ with mean V_{ave} MPH (miles per hour) and standard deviation V_{dev} MPH. Here, V_{min} is the minimum and V_{max} is the maximum moving speed of a vehicle. V_{max} is equal to the speed limit of the highway.

Fig. 3.1 The highway model

Vehicles running on the road are assumed to perform normal driving behaviors, such as acceleration, deceleration, overtaking, lane change,

merging and detouring. Considering two adjacent vehicles in the same lane cannot be too close to one another for the sake of safety, we assume that two neighboring vehicles in a same lane have to keep a predefined safe distance D . D is the lower bound of the distance between a vehicle and its front and back neighbors in a same lane. We also assume that each vehicle randomly generates a moving speed when it enters the highway and keeps this speed for a distance d_l (random variable). After the distance d_l is reached, the vehicle is allowed to change its moving speed based on the distance from its front neighbor. If the distance from the front vehicle is larger than the safe distance D , the vehicle is allowed to increase its moving speed with probability P_l . The new speed cannot be over the speed limit in any condition. If the distance between the two adjacent vehicles in the same lane is equal or shorter than the safe distance even the distance d_l is not reached, the back vehicle has to decrease its moving speed to keep the distance from its front vehicle having at least the safe distance.

Similar to the moving speed change, a vehicle can change the lane after moving a distance d_2 (random variable) with probability P_2 . However, if a vehicle is ready to change the lane, it must satisfy that there is no parallel vehicle in its target lane. After the lane change, the space between the vehicle and its front vehicle, and the space between the vehicle and its back vehicle will be adjusted automatically by the vehicles to satisfy the safe distance

constraint after sometime. We assume random variables d_1 and d_2 follow exponential distributions with means $E[d_1]$ and $E[d_2]$, respectively.

Vehicles may join the highway from entrances and detour from the exits. When a vehicle is merging to the highway from an entrance, it will insert into the right most lane (lane 3 in Fig.1) at first. Different from the normal lane change policy, vehicles entering the highway from the entrances are permitted to change the lane right away with probability P_3 without reaching distance d_1 . However, vehicles will follow the normal lane change policy introduced in the previous paragraphs after their first lane change attempt, and no matter they did or didn't change the lane. After entering the highway (no matter from the beginning or entrances), a vehicle is allowed to detour from an exit with probability P_4 . This exit would be randomly picked by the vehicle from the ones located after the entrance where it joined the highway.

3.3 V2V Communication Model

Our proposed V2V communication system is based on a clustering-based multi-channel vehicular ad hoc network. That is, all the vehicles in the system are self-organized into different clusters and the traditional common shared wireless medium is divided into multiple control channels and a single data channel. At the beginning, all the vehicles use control channels to organize

clusters. All the control channels are assumed to use IEEE 802.11 CSMA/CA protocol. The control channels also help clusters to achieve reconfiguration. Since each vehicle equipped with a GPS is assumed, the synchronization technique in a centralized network can be adopted inside each cluster of our proposed system. The data channel adopts a TDMA/CDMA MAC protocol. In clusters, each vehicle periodically reports its location information and moving speed to its Cluster Head (CH) during its own TDMA time slot by using data channel. The CH then broadcasts all the members' (including its own) location information and moving speeds to all the members via data channel. Since a CDMA technique is also utilized, each cluster has its own CDMA code so that there is no hidden and exposed terminal problem in the proposed V2V communication system.

3.3.1 Cluster-Self-Organizing Algorithm

In the proposed system, every vehicle belongs to one of the three possible statuses, namely CH, Cluster Member (CM) and Free Node (FN). The state transitions of a vehicle in clusters are shown in Fig. 3.2. In the next, we will introduce how a CH is elected and how clusters reconfigure in details.

Fig. 3.2 State transitions of a vehicle in clusters

In the initial phase (that means there is no cluster established in the system), all vehicles broadcast their location information, moving speeds, and vehicles' IDs (e.g., plate numbers or MAC addresses etc.) via the control channels by using IEEE 802.11 CSMA/CA protocol. After receiving neighbors' information, all the vehicles should have clear network topologic information. If we consider a three-lane highway system, all the vehicles in the middle lanes, will become CH candidates in the initial phase. (Note: in a two-lane highway system, vehicles in the right lane can be considered as CH candidates. In a four lane highway system, vehicles in any one of middle two lanes can be considered as CH candidates.) Vehicles in other lanes say in the first and third lanes lose the election if there is any vehicle in the middle lane, otherwise vehicles in the first lane or third lane can be CH candidates. Each CH candidate then generates a probability p (a random variable in the range $[0, 1]$), and broadcasts p by a control channel. The election of CH is based on

the comparisons of adjacent CH candidates' probabilities. The CH candidate with the highest probability p among its one-hop neighbors becomes CH, and the rest ones turn into CMs. However, their current statuses may change later. The detailed CH election procedures can be explained by the following example in Fig.3.3.

Fig. 3.3 CH elections procedure

In Fig.3.3, in the middle lane there are four vehicles, Vehicle 1 to 4. Vehicles 1 to 4 generated their own CH candidate probability as 0.1, 0.2, 0.5 and 0.3, respectively. Dot circles A to D indicate the transmission ranges of CH candidates 1 to 4, respectively. The following are the steps for CH election:

Step 1: Vehicle 1 compares its probability with Vehicle 2's. Since Vehicle 2's probability is higher than Vehicle 1's, Vehicle 1 becomes a CM of Vehicle 2 and Vehicle 2 keeps its CH candidate status.

Step 2: Vehicle 2 compares its probability with Vehicle 3's. Vehicle 2 finds its probability is smaller than Vehicle 3's probability. Thus it becomes a

CM of Vehicle 3. Then Vehicle 2 informs Vehicle 1 this change. Since Vehicle 2 changes to a CM of Vehicle 3, Vehicle 1 has to change itself back to a CH candidate. Since Vehicle 3 has higher probability than Vehicle 2, it keeps its CH candidate status.

3.3.2 Cluster Maintenance and Reconfiguration Protocols

As shown in the Fig. 3.2, there are four possible clustering-state transitions on each vehicle besides a FN is elected to be the CH. The cluster maintenance and reconfiguration protocols will be introduced in depth as follows.

1. ***FNs join existing clusters to become CMs.*** A vehicle's default clustering state is Free Node (FN) when it joins the highway from the very beginning or from an entrance. It broadcasts HELLO beacons periodically in the control channels wishing nearby CHs could hear. A HELLO beacon consists of two parts: join-cluster request and FN's moving information, which are shown in Fig.3.4. If a nearby CH hears FN's HELLO beacons, it will response a WELCOME message, and allows this FN to join its cluster. The FN's TDMA time slot assignment will be included in the WELCOME message to enable it communicates with other CMs right after joining the cluster. The composition of WELCOME message is described in Fig. 3.5. If a FN received two or more WELCOME messages from different CHs, it will

Join-cluster request	moving information
----------------------	--------------------

Fig. 3.4 Composition of a standard HELLO beacon

choose one with closer distance to join. If two or more CHs have the same distance to FN, the one with less CMs will be picked.

Cluster Information	CH's Information	FN's TDMA slot
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Fig. 3.5 Composition of WELCOME message

2. *CMs leave current cluster to become FNs.* CMs are required to report their moving information in every TDMA frame inside a cluster. If the CH does not hear from a specific CM for continuous N frames, this CM is believed that has left current cluster. However, CH will reserve its TDMA slot for another N frames to see if there is any new FN willing to join this cluster. If no HELLO beacon is heard when the time is expired, CHs will reschedule the TDMA time slots for the CMs whose time slots are behind the left one. The left CM will become a FN before it joins other clusters.

3. *CHs left current cluster.* A CH may leave the highway or move out its cluster, both of which cause the cluster to fall apart. If CMs did not hear the response from a CH for continuous N TDMA periods, this CH is supposed to leave current cluster. All CMs in the cluster will turn into FNs, and begin broadcasting HELLO beacons to start a new round of CH election.

4. ***Clusters Merge.*** If two CHs are too close to each (distance between two CHs is less than $1/d_m$ signal range), these two clusters will be merged. The CH in bigger cluster will automatically be elected as the CH in new cluster, and CH in the smaller cluster will become a CM. CMs in the disappeared cluster will still keep their CM states in the new one. If there is any CM which is outside the signal range of new CH, it will become FN and begin to broadcast HELLO beacons to find another cluster to join.

3.3.3 Intra- and Inter-Cluster Communication Protocols

In the proposed system, the IEEE 802.11 CSMA/CA protocol is used for control channels to coordinate new CMs joining and the inter-cluster communication among neighboring CHs. After a cluster is formed, all the intra-cluster communications between CMs and the CH in a cluster is accomplished through data channel. For the data channel, TDMA/CDMA technique is adopted. Each CH decides the TDMA frame structure based on the number of CMs in the cluster and numbers of neighboring CHs. The time slots in a TDMA frame are designed for all the CMs, current cluster's CH, other adjacent CHs if available, and some reserved slots. The reserved time slots locate in the tail of each TDMA frame. By doing this, whenever there is a FN becomes new CM to current cluster, the CH doesn't need to re-organize the TDMA slots for all the CMs, but assign a reserved slot to the new CM. The

details of a TDMA frame are shown in Fig. 3.6.

CDMA technique adopted in the system is to avoid the hidden and exposed terminal problems. Similar to the cluster self-organization algorithm, CHs can select different orthogonal codes with its neighboring CHs. Each CH is designed to have dual transmission powers. That is, when a CH needs to communicate with its CMs, the CH selects a short range transmission power. Otherwise, the CH uses a long range transmission power while it needs to exchange information with its neighboring CHs.

Fig. 3.6 TDMA frame structure

After the TDMA frame structure and CDMA code are formed, CH and CMs in a cluster start exchanging their location information and moving speeds using their own TDMA time slots. CMs are required to report their information in every TDMA frame in order to maintain the cluster and keep the moving information real-time. Since TDMA scheme is used as the MAC

protocol inside every cluster, the access delay for every vehicle is bounded to an acceptable range, which is the total length a TDMA frame in the clusters. What is more, TDMA scheme guarantees that there is no unpredictable backoff period and the possibility of packet collision is very low. All signals inside a cluster are encrypted by using the CDMA code of current cluster. Even though a vehicle could hear two signals from different CHs synchronously, there will be no collision happen in the vehicle since these two signals used different CDMA code to encrypt their information. That is to say there will be no hidden or terminal problem in our proposed V2V communication system, Fig. 3.7. The CH also handles new member joining and old member leaving processes.

Fig. 3.7 Intra- and Inter-cluster communications

3.3.4 Vehicle Accident Avoidance Mechanism (VAAM)

Since all the CMs including the CH in a cluster exchange their location information and moving speeds in every TDMA frame, all the vehicles should have the real-time moving and position information of their neighbors. When a driver tries to change current driving status, the pre-deployed Vehicle Accident Avoidance Mechanism (VAAM) in a vehicle will automatically judge whether this behavior is safe or not. If there is any potential danger, such as current speed is over limit, vehicle is too close to its front neighbor, or there is another vehicle in the blind area when changing lane, the VAAM system will raise an alarm to remind the driver to stop current attempts.

Besides danger reminding, the VAAM system will help drivers to know the emergency in advance. If there is any emergency happened, such as traffic accidents, traffic jams, and bad road conditions etc., the CH which is nearest to the emergent area uses long range transmission power to inform the CHs behind it. Following CHs pass this emergency information down to other CHs through control channels using long range transmission power. Each CH packs the emergency information into its own data packets, and informs its cluster members by using data channel. By this way, if the whole system can be one network topology, all the vehicles approaching the emergent area will know what happened exactly in advance, and make a decision early, like

slowing down, changing lane, or even detouring.

3.4 Summary

In this chapter, we introduced our clustering-based multi-channel V2V communication system in detail. At first, the importance of designing an efficient and fast V2V communication system was presented. We analyzed the drawbacks of contention-base and contention free MAC protocols to prove that neither of them was perfect enough to support traffic safety in VANETs. In the next, the highway and traffic model used in the proposed V2V communication was described. We tried our best to make this traffic model as close to the real-world situation as possible, so that our proposed system can be deployed in any type of road condition. Then, the detail of cluster head election algorithm and cluster-reconfiguration protocol was introduced carefully. At last, we focused on the description of the intra- and inter-vehicle communication protocol. A TDMA/CDMA hybrid protocol has been proposed to support the medium access in data channel. What is more, the VAAM that based on the V2V communication system to support traffic safety is presented in the last part of this chapter. To sum up, this chapter is the core part of this thesis.

Chapter 4

Simulation Results and Discussions

4.1 Introduction

In this chapter, we present comprehensive simulation results and discussions for the proposed clustering-based multi-channel V2V communication system.

The simulation is based on an event-driven simulator implemented by C++ language. The simulator is composed of two major parts: the traffic generator and the V2V communication simulator. The traffic generator successfully simulated the sophisticated highway traffic model we introduced in chapter 3. Rather than only allow vehicles to move at a constant and unchangeable manner on the highway like most of other researches, our traffic generator set the vehicles free to perform real driving behaviors, such as acceleration, deceleration, lane change, merging and detouring. The V2V communication simulator works as an add-on to the traffic generator. Vehicles perform

cluster-self-organization, cluster reconfiguration, inter- and intra-cluster communication using TDMA/CDMA hybrid MAC protocol automatically in our communication simulator.

The well-considered design and implementation of our simulator not only makes our simulation results more convincing and meaningful, but allows the proposed V2V communication system be implemented in any kind of road condition.

4.2 Simulation Parameters

The total length of simulated highway is assumed to be L . For each lane, the traffic stream follows Poisson distribution with mean rate λ_1 . Vehicles entering the highway from entrances also follow Poisson distribution. The mean arrival rate is fixed to λ_2 . The moving speeds of vehicles follow a truncated normal distribution in the range $[V_{min}, V_{max}]$ with mean V_{ave} MPH (miles per hour) and standard deviation V_{dev} MPH. According to [42], drivers' average reaction time to an emergency is between 0.75s to 1.5s. Considering the average moving speed in a highway circumstance is 60 MPH (roughly equals to 26.7 meters/s), the safety distance D between two adjacent vehicles is assumed to be 30 meters. The specific values of traffic model can be found in Table 4.1.

The IEEE 802.11-based wireless network cards are assumed to be used for

inter-vehicle communications, and the total wireless bandwidth is set to 11 Mbps [43], which 9 Mbps is reserved for single data channel and the rest 2 Mbps is used for control channels. In the simulation of the IEEE 802.11 CSMA/CA MAC protocol, time is slotted with a slot size α , and the packets are only allowed to transmit at the beginning of every slot. We assume that a DIFS duration is β , a SIFS duration is γ , and the transmission time for ACK is δ . In the simulation of TDMA/CDMA MAC protocol for data channel, Walsh codes are chosen for CDMA coding, and there are 64 Walsh codes in all, which are more than enough for the system. The reserved slots for free accessing are fixed to 3 TDMA slots, which are believed to satisfy both performance and efficiency. The details of parameter values in MAC protocols can refer to Table 4.2.

TABLE 4.1 Traffic Model Parameters

Parameters	Values
Highway lanes	3
Lane width	5 m
Highway length	10 miles (16000m)
Vehicle length	4 m
V_{min}	55 MPH
V_{max}	65 MPH
V_{ave}	60 MPH
V_{dev}	5 MPH
Safe distance D	30 m
$E[d_1]$	1.5 miles
$E[d_2]$	2.5 miles
Speed change probability P_l	90%

Lane change probability P_2	70%
Merging lane change probability P_3	50%
Cluster reconfiguration waiting time N	3 TDMA frames
Traffic stream (beginning) mean rate λ_1	0.5~4.5 vehicles/s
Traffic stream (entrance) mean rate λ_2	0.5 vehicles/s

TABLE 4.2 TDMA/CDMA MAC Parameters

Parameters	Values
Wireless channel bandwidth	11 Mbps
Data channel bandwidth	9 Mbps
Control channel bandwidth	2 Mbps
Number of control channels	5
Bandwidth per-control channel	400 Kbps
Data channel package size	512 Bytes
Control message package size	128 Bytes
Intra-cluster radio range (short)	100 m
Inter-cluster radio range (long)	250 m
Time slot duration α	1 ms
DIFS duration β	3 ms
SIFS duration γ	1 ms
ACK transmission time δ	5 ms
TDMA time slot size	5 ms
TDMA frame reserved slot	3 TDMA time slot
Usable CDMA codes	64

4.3 Simulation Results and Discussions

In order to systematically and quantitatively evaluate the performance of proposed V2V communication system, the metrics are carefully picked. Not

only the performance of MAC protocols are simulated, but also the topology-based metrics, such as average cluster size and average CH lifetime are evaluated. After the clusters are formed, TDMA MAC scheme is used as intra-cluster data channel protocol, which means the throughputs and transmission delays are stable and bounded on data channel. Therefore, most simulation attentions are focused on control channels' performance, which directly affects the transmission delay and performance of entire system. Simulation results are carefully compared with IEEE 802.11a, the suggested MAC protocol in DSRC (Dedicated Short Range Communications). Because the IEEE 802.11a MAC protocol only works on the single channel, it would be unfair if we only compare our proposed protocols with it. Hence, another clustering-based multichannel MAC protocols (CBM-MAC) proposed in [41] is used as a metric in some comparisons.

Fig. 4.1 illustrates the average number of vehicles in a cluster versus average arrival rate of traffic flow. It is clear to see that the cluster size is linearly increasing with the growing traffic load. It is because heavier traffic load means higher traffic density on the highway. The transmission range of vehicles are fixed, and that is to say higher traffic density equates to more cars in a given circle range.

Fig. 4.1 Average cluster size

Fig. 4.2 shows the average CH lifetime against traffic load. The proposed clustering scheme is compared with the one used in CBM-MAC. From this figure, we observe that these two schemes have similar performance when the traffic density is low. However, the proposed cluster scheme reveals its big advantage when the traffic load grows up. This is expected because only one factor, duration time, is considered when electing the CHs and there is no reserved TDMA slot for new members in CBM-MAC. However, geographic positions and moving speeds are considered and carefully weighted to elect a CH, and reserved slots are used for new members in our clustering scheme.

Fig. 4.2 Average CH lifetime

The number of control channels is assumed to be five in our proposed system, which means the total bandwidth is evenly divided into five pieces for each control channel. More control channels mean less possibility to wait for an out-going packet, but smaller bandwidth leads to slower transmission. Five is not a randomly-picked number, but a careful decision after evaluating the throughput and access delay of control channels while the number of control channels is increasing from 1 to 9. Figs. 4.3 and 4.4 show the throughput and access delay of control channel in the initial phase versus the traffic load respectively. The control channel throughput is defined as the percentage of total time occupied by successfully transmitted packets compared to simulation time. The access delay is the combination of the time segments of a packet from generated to be transmitted plus the propagation delay. From the results, we can see the increasing of benefit is markedly slowed down after five channels. This can be explained that the maximum cluster size is around

28 vehicles per cluster and five control channels are sufficient for vehicles' needs. Thus, channels more than five are redundant and bring little benefit.

Fig. 4.3 Throughput of control channels

Balanced the lost and gain, we choose five control channels in the proposed system. From Fig. 4.4, we can also find out that the access delay of control channels is no more than 200 ms when there are five control channels. This delay is believed to be short enough in VANETs, and can serve the V2V communication system which asks for fast medium access very well.

Fig. 4.4 Access delay of control channels

Fig. 4.5 shows the control channel performance with 1 control channel, 3 control channels and 5 control channels in different bandwidths. From Fig. 4.5 (a) to (f), we notice that 2 Mbps is the best choice for control channel bandwidth, which means best balance between bandwidth and throughput. This result stands for the decision we made to choose 2 Mbps as the total control channel bandwidth.

(a). Delay of 1 control channels in different bandwidth

(b). Throughput of 1 control channels in different bandwidth

(c). Delay of 3 control channels in different bandwidth

(d). Throughput of 3 control channels in different bandwidth

(e). Delay of 5 control channels in different bandwidth

(f). Throughput of 5 control channels in different bandwidth

Fig. 4.5 Different control channel performance in different bandwidth

Fig. 4.6 Probability of safety message delivering failure

Fig. 4.6 illustrates the impact of increasing traffic load on the probability of safety message delivering failure. The results from TDMA/CDMA MAC protocols are compared with IEEE 802.11, V2V-DCA which is another multi-channel MAC protocol based on Dynamic Channel Assignment (DCA) [43] and CBM-MAC designed in [41]. The soaring failure probabilities of the IEEE 802.11 and V2V-DCA are expected, because hidden and exposed terminal issues in multi-hop scenario are getting worse when the traffic load is heavy. Proposed TDMA/CDMA scheme has slightly better performance than already impressive CBM-MAC. Since TDMA Mac scheme is adopted inside every cluster in our proposed TDMA/CDMA MAC protocol, each vehicle has its own TDMA time slot to transmit data. Thus, there is little chance for collisions to happen. That is to say, the possibility of safety message delivering failure in our system is very low. Delivering failures may only happen when the clustering architecture is changed during the data transmission, such as a CM moves out of current cluster when it is sending information to CH, or the CH leaves current cluster when it is receiving data from a CM. This result showing in Fig. 12 can be explained by the complete resolve of hidden terminal issue in the proposed system. The only possibility that safety message delivers failure happens when the structure of clusters changed.

4.4 Summary

In this chapter, we have extensively analyzed the performance of newly proposed clustering-based multi-channel V2V communication system. Not only the performance of MAC protocols is considered, topologic metrics, such as average cluster size and average CH lifetime, is also attracted a lot of attentions. Compared to the clustering scheme used in CBM-MAC, new clustering scheme has more stable CHs and less cluster reconfiguration due to more factors were considered in the CH elections. 2Mbps bandwidth is reserved to five control channels. The decision is based on carefully evaluating the performance of control channels in different parameters and balancing the lost and gain. At last, our simulation demonstrates the proposed TDMA/CDMA MAC protocol has lowest message delivering failure rate compared with IEEE 802.11a, V2V-DCA and CBM-MAC. Therefore, the newly proposed V2V communication system is not only efficient and fast enough to support traffic safety, but also more stable and reliable.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis, we focused on designing an efficient V2V communication system based on VANETs to enhance traffic safety. We clearly realize that safety-related information in VANETs requires fast medium access and short end-to-end transmission delay. Thus, designing a fast MAC protocol is the key issue that determines the efficiency of V2V communication system. We carefully analyzed IEEE 802.11 CSMA/CA MAC protocol, which is the recommended MAC protocol for VANETs. Its biggest advantage is not sensitive to the topologic change which is good news for VANETs, and is easy to be operated in a fully distribution circumstance with acceptable performance when the traffic load is light. However, it suffers from a large number of packet losses and unbound access delay due to collisions and randomly backoff, which are the common problems of contention-based MAC

protocols. As an alternative, contention-free MAC protocols, such as TDMA, CDMA, token rings [44] etc., benefit their bounded delay and low rate of packet losses. However, how to achieve synchronization and reduce overheads are the most important problems that should be addressed before they can be deployed in VANETs.

Based on these observations, an idea of designing an hybrid MAC protocol that integrate the advantages of both contention-based and contention-free MAC protocols came to our mind. In this paper, we have proposed a clustering-based multi-channel V2V communication system to provide vehicle accident avoidance mechanism in order to enhance traffic safety. A self-cluster-organizing algorithm has been proposed to coordinate the cluster head election and cluster reconfiguration. The common shared medium in ad hoc networks has been divided into multiple control channels and a single data channel. The IEEE 802.11 CSMA/CA protocol has been used by control channels to accomplish the inter-cluster communications among neighboring cluster heads. A novel TDMA/CDMA scheme has been proposed for data channel to guarantee low end-to-end delay for intra-cluster communications.

Our performance analysis has demonstrated that the newly proposed clustering scheme has better performance than the one used in CBM-MAC [41], which brings longer-life cluster heads and more stable clusters. Further, the proposed TDMA/CDMA MAC protocol has shortest end-to-end delay and

lowest rate of packet delivering failure as compared to IEEE 802.11a, V2V-DCA and CBM-MAC. The proposed V2V communication system has shown its remarkable performance even when the traffic load was heavy.

We determined that the better performance of this newly designed V2V communication system is due to three reasons, which are concluded as follows:

- a. Dramatically reduced the overheads causing by clustering formation by adopting multi-channel technique.
- b. Achieved bounded access delay and low rate of packet losses by using TDMA scheme inside every cluster.
- c. Completely solved hidden/exposed terminal problems by introducing CDMA technique in inter-cluster communication.

All of these advantages make our clustering-based multi-channel V2V communication system is qualified and good enough to support traffic safety efficiently.

5.2 Future Work

In this research work, we successfully designed and simulated a sophisticated highway and traffic model, which allowed vehicles to perform real-world driving behaviors, such as acceleration, deceleration, lane change,

merging and detouring. This traffic model is believed to be more advanced than other similar models in VANETs. Considering our research focus is on the design of a V2V communication system, we have made some reasonable assumptions to simplify the traffic model. Therefore, it is possible to further investigate this model and introduce more sophisticated mechanisms. Possible options include considering two-way highway with corners and turns instead of one-way straight highway, and analyzing the impact to the proposed V2V communication system brought by the oncoming vehicles and more complicated road conditions. In addition, it is possible to study the traffic models that researched in transportation system and introduce more sophisticated traffic flow generation and control theories into our traffic model. We may replace the empirical parameters used in our traffic model with more accurate statistic data and formulas. All of these attempts are trying to make the proposed highway traffic model more close to the real-world situation, and make our simulation results more convincing.

The newly proposed CH election algorithm was based on the comparisons of adjacent CH candidates' probabilities p (a random variable in the range $[0, 1]$). This algorithm has been approved to be efficient in the initial cluster formation phase and can provide more stable cluster heads. However, there is still room for this algorithm to be improved. One of the drawbacks of this election algorithm is that the cluster heads elected will be very close to each

other, which means the clusters will be overlapped badly. This observation demonstrates that this newly designed algorithm is not optimized. Possible improvement is to consider more factors when choosing a cluster head. For example, it is possible to take factors like moving speeds, traveling time, and lane change frequency into consideration, and carefully weight these factors to obtain an optimized parameter to decide the new cluster head.

At last, the proposed V2V communication system is using multi-channel technique to resolve the overhead problem caused by cluster formation and reconfiguration; adopting TDMA scheme inside clusters to achieve bounded access delay and CDMA scheme to overcome hidden/exposed terminal problem. This system has been certified to be efficient enough to support traffic safety applications. The only potential complain about this system is the cost issue. Multi-channel technique requires one set of transmitter and receiver for each available channel. More channels brings better network performance, but more cost is expected. What is more, wireless communication devices used in our system requires supporting TDMA and CDMA scheme seamlessly. Even though it is not difficult to meet this requirement, this kind of devices is believed to be more expensive than others. How to deploy our proposed system in VANETs by an efficient and cheap way without sacrificing performance is still an open challenge to address.

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