AN EFFICIENT MAC PROTOCOL FOR PROVISIONING FAIRNESS IN VEHICLE TO ROADSIDE COMMUNICATIONS

By
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MASTER OF SCIENCE
IN
INFORMATION AND COMMUNICATION TECHNOLOGY

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Signature of the Candidate

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0413312010
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Dedication

THIS THESIS IS DEDICATED
TO
MY PARENTS AND FRIENDS
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List of Abbreviations

2D Two Dimensional
2G 2nd Generation
3G 3rd Generation
3GPP 3rd Generation Partnership Project
AC Access Category
ACI Adjacent Channel Interference
ACK Acknowledgement
AIFS Arbitration Inter Frame Space
AIFSN Arbitration Inter Frame Space Number
ASTM American Society for Testing and Materials
C2C-CC Car2Car Communication Consortium
CALM Communications Access For Land Mobile
CCH Control Channel
CCHI Control Channel Interval
CEN European Committee for Standardization
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
CTS Clear to Send
CW Contention Window.
DCF Distributed Coordination Function
DIFS DCF Inter Frame Space
DSRC Dedicated Short Range Communications
EC European Commission
EDCA Enhanced Distributed Channel Access
EDCAF Enhanced Distributed Channel Access Function
EDGA Enhanced Data rates for GSM Evolution
ETSI European Telecommunications Standards Institute
FCC Federal Communication Commission

x
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>GI</td>
<td>Guard Interval</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System.</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineering</td>
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<td>IFS</td>
<td>Inter Frame Space</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>IPv6</td>
<td>Internet Protocol version 6</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transportation System.</td>
</tr>
<tr>
<td>LLC</td>
<td>Logical Link Control</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MANET</td>
<td>Mobile Ad Hoc Network</td>
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<tr>
<td>MSM</td>
<td>Mixed Service Mobility</td>
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<tr>
<td>NAV</td>
<td>Network Allocation Vector</td>
</tr>
<tr>
<td>OBU</td>
<td>On Board Unit.</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
</tr>
<tr>
<td>PCF</td>
<td>Point Coordination Function</td>
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<tr>
<td>PHY</td>
<td>Physical</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
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<tr>
<td>RSU</td>
<td>Road Side Unit</td>
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<tr>
<td>RTS</td>
<td>Request to Send</td>
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<tr>
<td>SAE</td>
<td>Society for Automotive Engineers</td>
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<tr>
<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>SCHI</td>
<td>Service Channel Interval</td>
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<tr>
<td>SDO</td>
<td>Standards Development Organization</td>
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<tr>
<td>SIFS</td>
<td>Short Inter Frame Space</td>
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<tr>
<td>TC</td>
<td>Technical Committee</td>
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<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>TXOP</td>
<td>Transmission Opportunity</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>---------</td>
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<tr>
<td>V2D</td>
<td>Vehicle to hand-held Device</td>
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<tr>
<td>V2I</td>
<td>Vehicle to Infrastructure</td>
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<tr>
<td>V2V</td>
<td>Vehicle to Vehicle</td>
</tr>
<tr>
<td>V2X</td>
<td>Vehicle to Anything</td>
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<tr>
<td>VANET</td>
<td>Vehicular Ad Hoc Network</td>
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<tr>
<td>WAVE</td>
<td>Wireless Access in Vehicular Environment</td>
</tr>
<tr>
<td>WBSS</td>
<td>WAVE Basic Service Set</td>
</tr>
<tr>
<td>WIBSS</td>
<td>WAVE Independent Basic Service Set</td>
</tr>
<tr>
<td>WFQ</td>
<td>Weighted Fair Queuing</td>
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<tr>
<td>WG</td>
<td>Working Group</td>
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<tr>
<td>WiFi</td>
<td>Wireless Fidelity</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability of Microwave Access</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WSA</td>
<td>WAVE Service Advertisement</td>
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<tr>
<td>WSM</td>
<td>WAVE Short Message</td>
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<tr>
<td>WSMP</td>
<td>WAVE Short Message Protocol</td>
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</tbody>
</table>
List of symbols

\( P_{i,j,k} \) Probability of a vehicle of batch \( i \) is in backoff stage \( k \) with backoff counter value \( k \)

\( P_{\text{coll}(i)} \) Collision probability of batch \( i \)

\( P_{\text{idle}(i)} \) Channel idle probability when batch \( i \) has a packet to transmit

\( P_{\text{succ}(i)} \) Probability of successful transmission of batch \( i \)

\( P_{\text{drop}(i)} \) Packet drop probability of batch \( i \)

\( P_{\text{eqat}(i)} \) Probability that an vehicle of batch \( i \) has empty queue after successful transmission or packet drop

\( P_{\text{eq}(i)} \) Probability that an vehicle of batch \( i \) has empty queue

\( P_{\text{B}(i)} \) Probability of a vehicle is in batch \( i \)

\( W_{i,j} \) Contention window size of batch \( i \) at backoff stage \( j \)

\( CW_{\text{min}(i)} \) Minimum contention window size of batch \( i \)

\( CW_{\text{max}(i)} \) Maximum contention window size of batch \( i \)

\( m_i \) Maximum stage of batch \( i \) beyond which the contention window will not be increased

\( m_i + x_i \) Retransmission limit of batch \( i \)

\( P_{t(i)} \) Transmission probability of batch \( i \)

\( n_i \) Average number of vehicle of batch \( i \)

\( T_{\text{succ}} \) Average time of a successful transmission

\( T_{\text{coll}} \) Average time of a collision

\( \sigma \) Duration of a empty slot

\( T_p \) Average packet length in time

\( T_i \) Average residence time of batch \( i \)

\( S_i \) Saturation throughput of batch \( i \)

\( R_i \) Packet transmission rate of batch \( i \)

\( H \) Normalized throughput of the network

\( R_{\text{bit}} \) Bit rate over the channel
\( N_{bit} \) Average number of bit in a packet
\( N_p \) Average number of packet will be transmitted by the vehicle of batch 1
\( T_r \) Instantaneous residence time
\( R \) Radius of the coverage range of RSU
\( r \) Instantaneous distance of a vehicle from RSU
\( v \) Instantaneous velocity of a vehicle
\( v_{max} \) Maximum velocity in area of coverage range of RSU
\( v_{min} \) Minimum velocity in area of coverage range of RSU
\( T_{r(min)} \) Minimum residence time of vehicle
\( T_{r(max)} \) Maximum residence time of vehicle
Acknowledgment

All praises are for the almighty Allah for giving me the strength, without which I could not afford to attempt this research work.

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Abstract

Vehicular ad hoc network (VANET) is an important component of intelligent transports system (ITS) that facilitates variety of safety and non-safety applications. It has some unique characteristics, such as high geographically dynamic topology, predictable two direction mobility, varying vehicle density etc. Medium access control (MAC) protocol plays a vital role to share the common wireless channel efficiently among the vehicles in VANET. However, ensuring fairness is a challenging issue to design MAC protocols of VANET. Due to small residence time, existing IEEE 802.11 DCF protocol provides less opportunity for the vehicles with high velocity to communicate with road side unit (RSU), consequently allowing less amount of data be transferred compared to the vehicles low velocity. Existing MAC protocols take into account only velocities and can not ensure the data transmission rate to be proportional to residence time while providing minimum amount of data transmission for all vehicles irrespective of velocity. Therefore, an efficient MAC protocol, which takes position, direction and velocity of vehicles into consideration for ensuring minimum opportunity for all the vehicles, is yet to be proposed. In this research work, an efficient MAC protocol based on IEEE 802.11 DCF is developed which minimizes the unfairness problem of VANET. Unfairness problem has two aspects: higher velocity vehicles cannot transmit a minimum number of packets and lower velocity vehicles cannot transmit above a maximum number of packets. To address the above mentioned issues, the proposed MAC protocol adjusts the transmission probability for each vehicle according to its residence time by changing the value of MAC parameters (minimum contention window size, maximum backoff stage, retransmission limit, etc) dynamically. An analytical model is developed to analyze the performance of the proposed protocol. Analytical results show that the proposed scheme overcomes the limitations of existing MAC protocols by ensuring that packet transmission rate remains proportional to the residence time of the vehicles.
Chapter 1

Introduction

1.1 Vehicle Ad Hoc Network (VANET)

Vehicular ad hoc network (VANET) is a special type of mobile ad hoc network which consists of moving vehicles, stationary road side units (RSU) and hand-held devices. VANET is introduced as an important component of intelligent transport system (ITS) to support variety of safety and non-safety applications. VANET use either a single radio channel or multi-radio channel for communication in different networked environment such as vehicle to vehicle (V2V), vehicle to infrastructure (V2I) and vehicle to hand-held devices (V2D). VANET has some unique characteristics which constitute VANET as a distinct research field in MANET [1–6].

- **Geographically Highly Dynamic Topology:** Due to high node mobility, the network topology in a VANET changes very frequently.

- **Predictable Network Topology:** The movement of nodes in a VANET is somewhat predictable because node movement is constrained by the road topology.

- **Predictable Two Direction Random Mobility:** Nodes in a VANET can move at very high speeds (160 km/h), which might lead to frequent disconnection among nodes.

- **Unpredictable Radio Conditions:** Due to high node mobility, distance between transmitter and receiver varies with a short time so that transmitter cannot predict the actual distance from receiver.

- **Enough Battery Power:** Unlike MANET nodes, nodes in VANET have no energy limit.
• **Significant Storage Capacity**: VANET can provide sufficient storage due to high configure WAVE devices.

• **High Processing Power**: VANET can provide enough power from the power source of vehicles.

• **Strict Delay Constrains**: For safety application, it is guaranteed that the end-to-end delay of course not cross the bounded time and a minimum delay can tolerate by the non-safety application.

• **Varying Node Density**: The node density of a VANET may vary. The main challenge in rural areas is network disconnection, while scalability is the main challenge in high-density areas.

• **Faster Joining and Leaving Rate**: Due to high node mobility, joining and leaving rate of the vehicles in a particular RSU or a cluster is very high.

• **Infrastructure Support**: Unlike most MANETs, VANETs can take advantage of infrastructure on the roads. This could enhance the performance of VANET MAC protocols.

• **Availability of Location Information**: Location information can be provided by having a global positioning system (GPS) receiver on board.

• **Different QoS requirements**: IEEE 802.11p MAC protocol provides quality of service (QoS) for different types of safety and non-safety applications.

1.2 **Applications of VANET**

VANET is introduced for variety of safety and non-safety applications to provide traffic safety, traffic efficiency and infotainment services to the commuting passengers. The primary requirement of the safety applications is low latency and higher throughput for non-safety applications. Different forms of safety and non-safety applications are summarized in table 1.1.
<table>
<thead>
<tr>
<th>Safety applications</th>
<th>Event-driven safety applications</th>
<th>Traveler assistance</th>
<th>Public service</th>
<th>Event-driven safety applications</th>
<th>Periodic safety applications</th>
<th>Periodic vehicle-status reporting</th>
<th>Non-safety applications</th>
<th>Passenger infotainment</th>
<th>Driving assistance</th>
<th>Traffic efficiency and management</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Safety</td>
<td>Post-crash notification</td>
<td>Stolen vehicles tracking</td>
<td>Curve speed alert tracking</td>
<td>Safety warning</td>
<td>Safety warning</td>
<td>Non-safety applications</td>
<td>In-vehicle internet access</td>
<td>Online navigation</td>
<td>Toll payment services</td>
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<td></td>
<td>Event-driven</td>
<td>Predestrains crossing</td>
<td>Traffic flow control</td>
<td>Lane change alert</td>
<td>Cooperative collision warning</td>
<td>Periodic vehicle-status reporting</td>
<td></td>
<td>Mobile office</td>
<td>Smart parking</td>
<td>Real-time traffic notification</td>
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<td></td>
<td>safety</td>
<td>Parking spot locate</td>
<td>Approaching emergency vehicle warning</td>
<td>Lane marging alert</td>
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<td></td>
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<td>Media streaming</td>
<td>Remote vehicle diagnostics</td>
<td>Speed management</td>
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<td>applications</td>
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<td>Emergency break alert</td>
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</table>
1.3 Medium Access Control (MAC) Protocols for VANET

Medium access control (MAC) Protocol is responsible to share common medium among the participating nodes of the network. In VANET, a single radio channel is used by different nodes of the networks. Different unique characteristics of VANET impose several challenges to design MAC protocol [3].

- **Unfairness**: Due to relative motion between nodes, different priority of data, worse link between nodes, collision of data, unfairness problem is occurred in VANET.

- **Reliability**: One of the major challenges in the designing of the MAC protocol for VANET is to achieve reliable delivery of message.

- **Time-bounded Delivery**: An important requirement for MAC protocol in a vehicular environment is that it must be able to ensure delivery of safety messages with an upper bound time delay.

- **Efficiency**: The MAC layer plays a crucial role in regulating the access to the shared wireless medium so that multiple stations can share it efficiently.

- **Robustness**: The MAC protocol designed to elevate channel access mechanism must be robust enough to handle hidden terminal and exposed terminal problems.

- **Distributive**: It should pose minimal dependency on the RSU, that too with an efficient handoff protocol from one RSU to another.

- **Scalability**: The MAC protocols should be designed to support under different traffic load conditions.

- **Packet Reception Probability**: The MAC protocol should ensure that messages are actually received (no lost packets) and delivered only once (no duplicate packets), and are received in the proper order.

- **Priority**: Priority in managing access and communication time, the technique should be able to give priority to some stations over other stations to facilitate different type of services needed.
• **Transmission Collision Recovery**: If collision occurs, the protocol should be able to recover from the collision.

• **On Demand Channel Access**: The MAC protocol should ensure that the vehicle can access the channel on demand.

• **Effective Delivery of Packet**: The MAC protocol should ensure that the vehicles can transmit or/and receive packet effectively with number of retransmission as little as possible.

• **Time synchronization**: In order to be able to implement time-slotted MAC protocols, clock synchronization between vehicles in VANETs is an important issue.

• **Multichannel operation**: To ensure maximum connectivity and reduce collision, vehicles use different channels simultaneously.

• **Adjacent Channel Interference**: Adjacent channel interference (ACI) is occurred due to the parallel usage of the control channel (CCH) and the service channels (SCHs).

### 1.4 Motivation and Objectives

Transportation and automobile industry has been long anticipating the deployment of a complete autonomous vehicular network that will prevent accidents, facilitate eco-friendly driving, provide accurate real-time traffic information and offer entertainment services to the commuting passengers. Vehicular ad hoc networks (VANETs) is a special type of mobile ad hoc network which offers a promising passage to achieve this goal. In fact, the ability of vehicles to behave as mobile sensors and to relay data qualifies them to be indispensable in the process of inaugurating an intelligent transportation system (ITS). VANET is introduced in the form of vehicle to vehicle (V2V), vehicle to infrastructure (V2I) and vehicle to hand held device (V2D) communications, which are collectively referred to as vehicle to anything (V2X) communications [7].

Different nodes of the VANET share a common medium for data transmission. The medium access control (MAC) protocol is needed to share the common medium
among the nodes. The primary goal of an efficient MAC protocol in a VANET is to maximize the throughput for non-safety application while minimizing the access delay for safety applications. Due to the different velocity of the vehicles in the coverage area of RSU, the residence time variation between vehicles is occurred. Vehicles of less residence time do not get minimum chance to communicate with RSU and consequently transmit less amount of data as compared to the vehicle of high residence time. To support variety of safety and non-safety application, high velocity vehicles will be needed a minimum chance to communicate with RSU to fulfill at least safety application and other vehicles will be needed a certain chance for communication with RSU which is proportional to their residence time. It is ensured by a relative fairness called proportional fairness. IEEE 802.11p standard [8] defines MAC and PHY layer specifications for V2V communication of VANET. This standard does not consider V2I communication. IEEE 802.11 standard [9] used for V2I communication. This standard defines a MAC sublayer called distributed coordination function (DCF). IEEE 802.11 DCF protocol is a random access mechanism based on carrier sense multiple access with collision avoidance (CSMA/CA). IEEE 802.11 standard MAC protocol does not provide a minimum chance to high velocity vehicles for communication with RSU because same MAC parameters (minimum contention window, maximum backoff stage and retransmission limit) is used by all vehicles. This protocol is not suitable for safety applications. The protocol provides a certain chance to the vehicles which is proportional to their residence time and is more applicable for non-safety application. A modified IEEE 802.11 DCF based fair access MAC scheme is proposed in [10], which ensures the absolute fairness by providing equal chance to all vehicles for communication with RSU. This protocol consider that vehicle transmit only safety related message. Absolute fairness do not ensure fair access channel for both safety and non-safety applications of VANET. To resolve this problem an efficient IEEE 802.11 DCF based MAC protocol for vehicle to infrastructure/roadside (V2I) communication of VANET is proposed in this thesis work.

The goal of the research work is to overcome unfairness problem occurs due to velocity variation between different vehicles in vehicle to infrastructure (V2I) of VANET. To meet the goal, the following objectives have been identified:
To develop an efficient MAC protocol for VANET to ensure fairness.

To develop an analytical model for the proposed protocol.

To compare the results of proposed protocol with existing protocols.

1.5 Related Work

Performance analysis of the IEEE 802.11 DCF mechanism in either saturated or non-saturated state has been recently studied in the literature [11–16]. In [11], P. E. Engelstad et al. proposed a Markov chain model for the IEEE 802.11e EDCA mechanism to describe the normalized throughput, packet dropping probability and delay when the network is in a non-saturated state. In [12], D. Malone et al. proposed a Markov chain model for the IEEE 802.11 DCF mechanism to analyze the performance of the network when the network is in a non-saturated state and nodes have heterogeneous traffic. In [13], K. Duffy et al. proposed a Markov chain model for the IEEE 802.11 DCF mechanism to analyze the performance of the network when the network is in a non-saturated state and nodes have homogeneous traffic. In [14], T. H. Luan et al. presented a Markov chain based analytical model for IEEE 802.11 DCF based MAC protocol for V2I communications in saturated state and shows the impacts of mobile nodes on the system throughput. In [15], T. O. Kim et al. present Markov chain model for both IEEE 802.11 DCF and IEEE 802.11e EDCA scheme to find the normalized channel throughput, average packet HoL (head of line) delay, expected time to complete transmission of a flow and packet loss probability in non-saturated condition. However, none of the above work considers the unfairness problem for V2I communication in VANETs. Various TDMA based MAC protocols have been discussed in [17–28] which assign one-time slot to each active vehicle in different methods. Although several TDMA based MAC protocols [17–21] provide efficient packet delivery and fair channel access for fixed number of vehicles, they cannot handle both sparse and dense mobility scenarios. Moreover, majority of TDMA based MAC protocols [22–28] fail to achieve fairness for vehicles having high variance in relative motion. Moreover, these approaches need strict synchronization and can transmit only fixed length packets. In distributed TDMA based MAC, access collision and merging collision problems can occur between vehicles.
In centralized TDMA based MAC, one-hop neighboring collision and hidden node collision can arise between vehicles [29].

Proposal of MAC protocols based on IEEE 802.11 DCF to ensure fairness for V2I communications in VANET has been studied in [10, 30–34]. In [30], W. Alasmary et al. proposed two dynamic CW based mechanisms to alleviate the performance degradation caused by different velocity of vehicles. However, they do not describe the exact procedure for the selection of optimal contention window size to avoid unfairness problem. In [10], to address unfairness problem, E. Karamad et al. proposed a modified IEEE 802.11 DCF based MAC protocol which dynamically assigns minimum contention window to each vehicle batch at the beginning of accessing the network for the whole residence time by adjusting transmission probability with its speed. They ensure absolute fairness considering the network is in a saturated state. Moreover, they derived some relations between average velocity and the minimum contention window of each batch through analytical approximations. Performance analysis of this model, which is based on Bianchi model [35] has the following assumptions:

1. Every node of the network always has at least one packet to transmit.
2. There are no hidden terminals and exposed terminals in the network and no capture effect.
3. Each packet collides with constant and independent probability regardless of current state of the node.
4. Transmission channel is ideal and transmission errors occur due to packet collision only.

In [31], Q. Wu et al. presented a MAC protocol proposed by E. Karamad et al. [10] and analyzed the performance by considering the network is in a non-saturated state. Moreover, they derived the relationship between the transmission probability and the minimum contention window size of a vehicle and the relationship between the average velocity and the minimum contention window size of a vehicle in a non-saturated state. Both authors [10, 31] consider a network model with following assumptions:
1. The vehicles arrive in the network in batches according to Poisson process with constant rate.

2. The vehicles in each batch have same average velocity and velocity remains constant for whole residence time of a particular RSU.

3. Moving direction of each vehicle does not change and batch no of a vehicle remains same for whole residence time.

Both authors [10,31] ensure the absolute fairness of the network which is appropriate for safety applications only. They do not ensure the proportional fairness of the network which is needed for both safety and non-safety applications.

In [32], V. P. Harigovindan et al. derived the analytical expression for optimum CW required to ensure fairness, in the sense of equal opportunity to communicate with RSU among the vehicles of different average velocity in the network. However, they do not analyze the network performance of the network in both saturated and non-saturated state. Although, this protocol can achieve the absolute fairness but do not consider the proportional fairness which is required for both safety and non-safety applications.

To address unfairness problem of V2I communications, Hoeft et al. [33] proposed a RSU selection algorithm to obtain even attachment of OBUs to RSUs and to minimize the variation of OBUs connected to each RSU. However, they do not solve the unfairness problem among vehicles with different velocities for a particular RSU. In [34], Zhang et al. build a Mixed-Service-Mobility (MSM) model for IEEE 802.11p scheme to analyze the interaction between delay-tolerant services and real-time services under high speed mobility condition instead of four different access categories (AC) defined by IEEE 802.11p standard. Although they ensure longtime fairness for delay-tolerant services but do not achieve fairness for real time services.

1.6 Organization of Thesis

The subsequent parts of the thesis are organized as follows:

**Chapter 2** of this thesis work covers a detail overview of the vehicular communications which includes standardization of vehicular communication, overview of
WAVE. Medium access control (MAC) protocol and fairness in resource allocation is also discussed in this chapter.

Chapter 3 presents an efficient IEEE 802.11 DCF based MAC protocol to ensure the fairness for V2I communication of VANET. A Markov chain model for the proposed protocol is analyzed in this chapter.

Chapter 4 investigates the performance between proposed techniques and existing methods in terms of performance parameters in terms of number of transmitted packets. Transmission probability, channel idle probability, packet drop probability are also investigated for different batch vehicles. Individual throughput of each batch and overall throughput of vehicles are investigated to show the achievement of proportional fairness.

Chapter 5 concludes the thesis and recommendations for future work is also available in this chapter.

1.7 Summary

This chapter introduces a brief introduction of VANET with its background. An analysis of some related coexistence issues of VANET are included here. Motivations for carrying out this research work are also outlined here. Consequently and research objectives are presented. Finally, organization of the thesis is briefly described.
Chapter 2

Overview of Vehicular Communications

2.1 Introduction

In this chapter an ultimate overview is given to WAVE standards of VANET. This chapter gives the detailed overview about IEEE 802.11 standard, IEEE 802.11p standard MAC protocol and as well as the overview of fairness scheme of wireless network.

2.2 Standardization on Vehicular Communications

Much has happened during the last two decade within all major Standards Development Organizations (SDO) and industry organizations dealing with vehicular communications. In this section, the recent standardization efforts and related activities in the field of VANETs is presented.

- DSRC

Dedicated Short-Range Communication (DSRC) [36] initially coined in USA by the FCC (Federal Communication Commission) [37]. DSRC is a suite of standards at the heart of the communication of vehicular safety messages. The fast exchanging of safety messages, combined with knowledge about other moving vehicles that may not be visible to drivers in a timely manner extend the safety concepts beyond the dreams of most of the public [38].

The history leading to the development of current DSRC goes back almost two decade and a half. In the early 1990s, it became clear that road toll collection can be simplified by means of RFID transponders. The group of electronic toll suppliers along with other stake holders formed a consortium focused on
DSRC development [39]. The DSRC community then attempted to standardize the 915MHz using the ASTM framework but quickly thought of the IEEE 802.11 approach and the 5.9GHz as a direct way to benefit from its ad hoc mode. The ad hoc mode of IEEE 802.11 resembles the situation of vehicle to vehicle communications and hence, simplifies the development of DSRC.

- **ASTM**
  The American Society for Testing and Materials (ASTM) was commissioned to bring forward a standard and they did so by emanating from the WLAN standard IEEE 802.11 and made some minor changes to fit it to the high-speed vehicular environment. It was approved in 2003. The ASTM standard [40] made use of a simple mailbox application layer [41] and the resulting protocol stack contained three layers: application, data link and physical.

- **SAE**
  The Society for Automotive Engineers (SAE) is developing a message set dictionary [42] to be used by road traffic safety applications. The SAE is also developing a minimum performance requirements document J2945.1 [43], which will be the basis for road traffic safety applications.

- **IEEE WAVE**
  In 2003, IEEE took over the work from ASTM and they have extended the protocol stack with more layers for supporting Internet access and so forth. This more holistic view has been given the name wireless access in vehicular environment (WAVE) and it includes the physical layer up to the transport layer. The WAVE approach will be discussed in detail in Section 2.3.

- **TC204/WG16-CALM**
  The International Organization for Standardization (ISO) is developing a framework called communications access for land mobiles (CALM) [44]. The idea with CALM is to use all types of already existing wireless access technologies
such as 2G, 3G, EDGE, GPRS, LTE, WiMAX, Wi-Fi, DSRC to provide broadcast, unicast, and multicast communications between mobile nodes, between mobile nodes and the infrastructure, and between fixed infrastructures. For supporting vehicular ad hoc networking, CALM M5 [45] has been developed, which is based on IEEE 802.11p. CALM M5 is intended for real-time road safety applications requiring bounded access channel delays and low communication overhead. The low overhead network and transport layer protocol has been developed called CALM – Non-IP networking [46].

**ETSI TC ITS**

In 2007, ETSI has established a Technical Committee TC ITS (Intelligent Transportation System) in order to develop standards and specifications for the use of communication technologies in transport systems. In 2009, the European Commission (EC) issued mandate M/453 [47]. ETSI and CEN responded to the mandate, which is legally binding. ETSI is responsible for developing the whole protocol stack including vehicle-centric road traffic safety applications, whereas applications orienting towards road traffic efficiency utilizing road infrastructure are under the responsibility of CEN. In Europe, 30 MHz has been set aside for vehicular communications at 5.875-5.905 GHz, solely intended for road traffic safety applications. Non-safety related applications are directed to a 20 MHz band at 5.855-5.875 GHz. The dedicated frequency bands have been divided into 10 MHz frequency channels. Due to the proximity of these bands to the frequency band used for ETC in Europe (5.795-5.805 GHz) ETSI TC ITS must also develop mitigation techniques to avoid to interfere with the ETC systems [48]. There is no cost associated with using this frequency 10 band (it is license free). However, the usage of it is regulated in EN 302 571 [49] specifying requirements on output power limits, spectrum masks etc.

**C2C CC**

Car2Car Communication Consortium (C2C-CC) is a nonprofit organization supported by industry, launched in the summer of 2002 by European vehicle manufacturers. C2C-CC aims to establish an open European industry stan-
standard, focused on development of active safety applications. The C2C-CC is backed by European automobile industry. C2C-CC is designing C2Cnet protocol that differs from IP. The protocol is destined to be used for both safety and non-safety applications. Also, a single protocol is being considered for use with both the infrastructure based and infrastructure less communication modes [50].

2.3 Wireless Access in Vehicular Environment (WAVE): An Overview

2.3.1 WAVE protocol Stack

The overall architecture of WAVE [51] is defined by IEEE 1609 family, IEEE 802.2 standard, IEEE 802.11p standard and the Society of Automotive Engineering (SAE) J2735 standard, as shown in figure 2.15.

![WAVE protocol stack](image)

Figure 2.1: WAVE protocol stack containing both safety and non-safety application part
2.3.2 IEEE 1609 Standards suite for WAVE

IEEE 1609 suite of Standards define the different layers and sublayers of WAVE protocol stack which are shown in below.

- IEEE P1609.0 specifies the architecture of WAVE.
- IEEE 1609.1 specifies the resource manager of WAVE.
- IEEE 1609.2 specifies the security services for applications and management messages of WAVE.
- IEEE 1609.3 specifies the networking services of WAVE.
- IEEE 1609.4 specifies multi-channel operations of WAVE.
- IEEE 1609.5 specifies communication manager of WAVE.
- IEEE 1609.6 specifies remote management services of WAVE.
- IEEE P1609.11 specifies over the air data exchange protocol of WAVE.
- IEEE P1609.12 specifies identifier allocations of WAVE.

2.3.3 IEEE 802 Standards for WAVE

- IEEE 802.2 specifies Logical Link Control (LLC) sublayer of WAVE.
- IEEE 802.11p specifies medium access control (MAC) sublayer and physical layers (PHY) of WAVE.

2.3.4 SAE Standards for WAVE

- SAE J2735 specifies a message set for safety application of WAVE [42].
- SAE J2945.1 specifies the minimum performance requirements and the standard features used on the interface required to establish interoperability between on-board units for V2V safety systems [43].
2.3.5 WAVE System Components and Connectivity

A WAVE system provides connectivity in support of stationary and mobile (e.g., pedestrian and in-vehicle) applications offering safety and convenience to their users.

IEEE 1609 standards specifies different types of WAVE devices, such as (a) moving on board units (OBU) with Global Positioning System (GPS) receiver located inside the vehicles (b) stationary roadside units (RSU) placed on the roadside (c) hand-held devices carried by pedestrian, cyclist, roadside workers, driver or passenger. RSUs are usually mounted in an elevated position on existing transportation infrastructure, such as traffic lights, street lights and road signs. WAVE devices, such as RSU, hand-held device and OBU, are expected to be implemented using two types of radio devices. First is a single channel WAVE device which transmits data and/or receives to only one RF channel at a time (commonly called single-channel device). Second is a multi-channel WAVE device that transmits data and/or receives to at least two channels at a time (commonly called multi-channel device).

Figure 2.2: WAVE network architecture
WAVE standards are intended to support a networked environment with low latency transactions for vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to hand-held device (V2D) communications, which are collectively referred to as vehicle to anything (V2X) communications, as recently defined by the Third Generation Partnership Project (3GPP) group [7].

WAVE uses two available service sets for network topology handling. Wave basic service set (WBSS) is defined for communication between RSUs and OBUs. The second service set is called WAVE independent basic service set (WIBSS). This service set supports the communication between two nodes in a mesh network i.e. V2V communication without the involvement of an RSU. Figure 2.2 represent the RSU communication zones. The OBUs move between communication zones and exchange information with RSU. To define different WAVE communication zones, each WAVE Basic Service Set (WBSS) use a unique identifier. Vehicles must associate with only one WBSS at a time.

2.3.6 WAVE Communication Modes

In the network layer, the routing protocol has to implement strategies that provide a reliable communication and do not disrupt the communication. Vehicular networks support different communication paradigms. These can be categorized as follows:

- **Unicast Communication**: the main goal is to perform data communication
Multicast/geocast communication: The main goal is to perform data communication from a source node to a group of target nodes. Geocast is a specialized form of multicast addressing, in which a message is sent to a group of target nodes in a particular geographic position. Generally, geocast...
communication mode is used in WAVE for safety application.

- **Broadcast communication**: the main feature is to have a source node sending information to all neighboring nodes at once. Generally, broadcast communication mode is used in WAVE for safety application.

### 2.3.7 WAVE Channel Coordination and Time Synchronization

Channel coordination is specified in IEEE 1609.4. In WAVE communications, time and frequency resources are segmented to provide a variety of safety and non-safety applications. WAVE devices have the ability to access one or more channels on an alternating basis. Alternating radio channel access is coordinated based on intervals that are synchronized relative to a common time base. The channel access time is divided into synchronization interval (SI) of 100 ms. Each SI consists of two alternating fixed length (50 ms including 4 ms guard interval) intervals, called the CCH interval (CCHI) and the SCH interval (SCHI), as shown in figure 2.6. A guard interval begins each CCH interval and SCH interval, during a guard interval a device that is switching channels is assumed to be unable to receive packets. During the CCHI, each node in a vehicular network tune to the CCH for WAVE short message (WSM), WSA messages and others control messages. A vehicle monitors the CCH, coordinates with the RSU or neighboring vehicles and then simply switches to a SCH. During the SCHI, some vehicles tune to a SCH based on WSA messages and receive safety and non-safety messages, and some nodes tune to a SCH base on their commitment on WSA message.

In addition to continuous (CCH or SCH) and alternating (CCH and SCH) channel

![Figure 2.6: Channel interval of multichannel operation of WAVE](image_url)
access, WAVE standards allow immediate and extended access, as shown in figure 2.7. The WAVE device providing the service would be expected to have a radio in SCH continuous access to support the extended transaction. The provider indicates in the WSA channel information whether it supports continuous or alternating access on the SCH, or this information is known a priori by the user. A single-radio device using alternating channel access synchronizes to a standard time base. Channel timing is defined such that a synchronization (SI) interval begins at the start of a second in Coordinated Universal Time (UTC). UTC or an equivalent is commonly provided by GPS. The timing advertisement frame specified in IEEE Std 802.11-2012 is also used to convey an estimate of absolute time from one device to another for the purpose of synchronization.

2.3.8 Spectrum Allocation for WAVE

The Federal Communications Commission (FCC) has allocated 75 MHz of spectrum in the 5.9 GHz (5.850-5.925 GHz) band for dedicated short-range communication (DSRC). Number of channels, transmitted power and application of channels are shown in figure 2.8. WAVE systems use these channel of DSRC, or a subset thereof. The DSRC spectrum is divided into seven independent (one control channel and
Figure 2.8: Channel allocation of WAVE

six service channel) 10 MHz channels (numbered as 172, 174, 176, 178, 180, 182 and 184) and one 5 MHz (5.850-5.855 GHz) reserved guard band. The pair of channels (channel 175 and 176, and channel 180 and 182) is combined to form a single 20 MHz channel, channel 175 and 181 respectively. The channel 178 is used as CCH to transmit WSMP messages and WSA messages. Channels 172 and 184 are designated for public safety applications involving safety of life and property. Specifically, channel 172 is for vehicle-to-vehicle safety communications and channel 184 is for high-power longer distance communications.

2.3.9 Modulation Method of WAVE

The IEEE 802.11p standard uses a physical (PHY) layer that is adopted from the IEEE 802.11a standard (i.e., changing the signal bandwidth to 10 MHz and operating frequency to the 5.9-GHz band). The IEEE 802.11a is an approved amendment to the IEEE 802.11 wireless local network specifications that defines requirements for an orthogonal frequency division multiplexing (OFDM) communication system. The basic idea of OFDM is to divide the available frequency spectrum into narrower subchannels (subcarriers). The high-rate data stream is split into a number of lower-rate data streams transmitted simultaneously over a number of subcarriers, where each subcarrier is narrow banded. There are 64 subcarriers, where 52 subcarriers (48 are data carriers, 4 are pilot carriers) are useful subcarrier and 12 are
null subcarriers. The null subcarriers are allocated in the beginning (0) and middle (27 to 37) of the band to eliminate the effect of null carriers in the data subcarriers. The useful subcarriers are assigned numbers from -26 to 26. The pilot signals are embedded into the subcarriers of -21, -7, 7 and 21 as shown in figure 2.9.

2.4 Medium Access Control (MAC) Protocol

2.4.1 IEEE 802.11 DCF Scheme

The IEEE 802.11 standard [9] species two MAC schemes: a mandatory Distributed Coordination Function (DCF) and an optional Point Coordination Function (PCF). The latter is a centralized MAC protocol that provides collision free and time bounded service. The former scheme, DCF is most widely implemented in WLAN technologies because it is simple and offers an efficient best-effort service. The DCF is the basic access method of the IEEE 802.11 MAC, and it is derived from carrier sense multiple access with collision avoidance (CSMA/CA). CSMA/CA is designed to reduce the probability of collision. The IEEE 802.11 standard specifies two access mechanisms for DCF: basic access mechanism and RTS/CTS access mechanism. Two-way handshaking technique is used as the basic access mechanism and four-way handshaking technique is used as the RTS/CTS access mechanism for packet transmission to protect hidden terminal problem.
2.4.1.1 Basic Access Mechanism of DCF Scheme

In the IEEE 802.11 DCF standard, the wireless nodes contend to access the sharing medium using a CSMA mechanism with collision avoidance. The basic access mechanism is described using the flow chat shown in figure 2.10. When a node has a packet to transmit, the backoff instant enters the backoff procedure and first selects a random backoff time from $[0, W - 1]$, where $W$ is the contention window size of the node. After the channel is sensed idle for a guard time called distributed inter-frame space (DIFS), the backoff time counter is decremented by one at the end of each idle time slot and frozen if a packet transmission is detected by the node on the channel. It is resumed again after the channel is sensed idle for DIFS period. When the backoff counter reaches zero, the node transmits the packet immediately. If ACK message returns after a short inter-frame space (SIFS), the transmission is considered successful and the backoff instant enters the new backoff procedure with minimum contention window size if the node already has a packet to transmit. After each successful transmission, the backoff instant enters the post backoff procedure if the node has no packet to transmit. The unsuccessful transmission or collision occurs when the backoff counter of two or more nodes reach zero in the same time slot. After every unsuccessful transmission, the backoff instant enters a new backoff procedure and doubles its contention window size. Then backoff instant selects a random backoff time from $[0, 2^j W - 1]$, where $j$ is the number of collision for a specific packet. The process of doubling the contention window size keeps on after each failure until reaching a maximum, $CW_{max}$. At this stage, if the transmission failure occurs again, the contention window is not doubled anymore. The node repeats the last stage of backoff process at most for a predefined retry limit and drops the packet if it has not been transmitted yet. At last, the contention window size is reset to its minimum value for the next packet to transmit. Figure 2.11 demonstrates the timing diagram of IEEE 802.11 DCF basic access mechanism.

2.4.1.2 Hidden Terminal Problem

Single-channel V2V and V2I networks suffer from the hidden terminal problem and only V2V networks suffer from the exposed terminal problem. Hence, VANETs require effective mechanisms for collision avoidance and fair contention resolution.
An example is shown in figure 2.12 to illustrate the hidden terminal problem. Vehicle $V_s$ and $V_h$ are the senders. Vehicle $V_h$ is in the range of the Vehicle $V_s$ but cannot hear Vehicle $V_s$. When both, vehicle $V_s$ and vehicle $V_h$ want to send packets to their common neighbor vehicle $V_d$, collisions occur at $V_d$ and it hears only garbled frames. In addition, it is generally seen that even the provision of "sensing the common channel before an attempt to access the channel" does not eliminate collisions. Thus, there is degradation in the performance of the network due to a
reduction in the network capacity for transmission of useful data. This scenario is referred to as the hidden terminal problem. It is said that vehicle $V_h$ is a hidden terminal from vehicle $V_s$. The hidden node problem causes unfairness in wireless networks.

2.4.1.3 RTS/CTS Access Mechanism of DCF Scheme

DCF defines an optional RTS/CTS mechanism which can reduce the probability of collisions caused by the hidden node problem. Figure 2.14 illustrates the timing diagram of RTS/CTS exchange scheme. The RTS/CTS mechanism is a four-way handshaking mechanism. A node needs to follow the medium access rules explained in 802.11 MAC layer when it has a packet to transmit. However, before sending a
data packet, this node needs to send a special short frame which is called a Request to Send (RTS). When the destination node receives this RTS frame, it will send back a Clear to Send (CTS) frame after a short period of time (SIFS – Short Inter Frame Space). The sending node can only transmit this data packet after it receives the CTS frame correctly. The NAV (Network Allocation Vector) is the duration of time that predicts how long the medium will be occupied for the transmission. NAV is contained in the MAC header of the RTS/CTS frame. All nodes (except the sender and the receiver) should update their NAV after receiving the RTS/CTS frames. These nodes are not allowed to sense the medium status until their NAVs are expired.

The following example explains the procedure of the RTS/CTS mechanism and presents how the RTS/CTS mechanism to solve the hidden node problem: $V_s$ will send a RTS frame before starting a transmission to $V_r$. Even though $V_h$ cannot hear this RTS frame, $V_r$ still can hear a CTS frame from $V_s$. This CTS frame contains the duration of the transmission from $V_s$ to $V_r$. $V_h$ knows the medium will be occupied by other nodes, and $V_h$ will defer its transmission until the duration is over [9].

The RTS/CTS mechanism can effectively ameliorate the hidden node problem, but the RTS/CTS mechanism is not used for every data frame transmission because the RTS/CTS frame exchange will cause additional transmission overhead. To mitigate the effect of the transmission overhead of RTS/CTS, IEEE 802.11 MAC protocol defines the RTS/CTS exchange as an optional mechanism. The use of the RTS/CTS mechanism is configured by the RTS threshold. If the length of the data
frame is longer than the RTS threshold, the RTS/CTS mechanism will be turned on; otherwise, the RTS/CTS mechanism will be turned off. In most IEEE 802.11 WLANs, a large value is set as the RTS threshold (e.g., 3000 octets) to disable the RTS/CTS mechanism.

2.4.1.4 Exposed Terminal Problem

To understand the exposed terminal problem, consider Vehicle $V_e$ which is in the range of the transmitter Vehicle $V_s$, but not that of receiver Vehicle $V_{d1}$. This is shown in Figure. With the regular carrier sensing mechanism, Vehicle $V_e$ will defer from accessing the shared channel when $V_s$ attempts to transmit to $V_{d1}$. Thus Vehicle $V_e$ is prevented from transmitting. Vehicle $V_e$ is the exposed terminal whose transmission to $V_{d2}$ is deferred. Collision is an important design challenge for VANET. At the time of collision, considerable amount of radio resources are wasted. This is because the source vehicle still continues to transmit the packet completely. The performance degradation due to these collisions tends to become more severe as the frame size increases, since the bandwidth wasted by collisions becomes relatively large. Hence, the amount of resources wasted in an ad-hoc network depends upon the size of the packet. Moreover, collisions cause retransmissions. This consumes a significant amount of energy, thus reducing the lifetime of battery-powered wireless devices. The problem of collision is worse in a multi-hop environment than in a single-hop environment. Collision Avoidance is implemented in the medium access control (MAC) layers.
2.4.2 IEEE 802.11p EDCF Scheme

The IEEE 802.11p standard uses a medium access control (MAC) layer that is adopted from the IEEE 802.11e EDCA standard. The IEEE 802.11e EDCA [8] is an extension to IEEE 802.11 DCF that provides service differentiation and quality of services (QoS). In EDCA, the node separates its arrival traffic into four categories, each one called an Access Category (AC). Each AC, numbered from 0 to 3,
has its own EDCA parameters, that is, inter-frame space duration, minimum contention window size, maximum contention window size, maximum backoff stages, retransmission limit, etc. The AC0 is the lowest priority class of service and AC3 is the highest priority class of services. AC3 is served before the others and AC0 is served after the others. Each AC queue works as an independent DCF node with enhanced distributed channel access function (EDCAF) to contend for Transmission Opportunities (TXOP) using its own EDCA parameters. Prioritization of transmission in EDCA is implemented by a new inter-frame space (IFS) called Arbitration Inter-Frame Space (AIFS) used in place of DIFS. AIFS is a function of the AC i.e., $AIFS(AC) = SIFS + AIFSN(AC) \times T_{slot}$, where AIFSN(AC) is an integer denoting the AIFS number of the corresponding AC, $T_{slot}$ denotes the duration of a time slot and SIFS is the short inter-frame space. Each node has four AC queues acting as four independent nodes. At first node separates its arrival traffic into four ACs and then place into corresponding AC queue. If the channel is sensed idle for the duration of AIFS[$x$] and if the AC$x$ queue has no data for transmission, the backoff instant does not enter the backoff procedure. Otherwise, the backoff instant enters the backoff procedure and first selects a random backoff time from $[0, W[ACx] - 1]$, where $W[ACx]$ is the contention window size of the access category $x$ ($AC_x$). After AIFS[$x$] time, the backoff time counter is decremented by one at the end of each idle time slot and frozen if a packet transmission is detected by the node on the channel. It is resumed again after the channel is sensed idle for AIFS[$x$] period. When the backoff counter reaches zero and no other packet from a higher priority category is ready to be transmitted, the node transmits the packet immediately. If the transmission is successful and the backoff instant enters the new backoff procedure with minimum contention window size if the AC already has a packet to transmit. If there is such a coincidence, the packet with higher priority is transmitted while the lower priority packet (s) experience a virtual/internal collision, that is, the packets in lower priority queues act as if a collision occurs. A scheduler inside nodes will avoid this kind of internal/virtual collision by granting the EDCF-TXOP to the highest priority AC. At the same time, the other colliding ACs will invoke the backoff procedure due to the internal collision and behave as if there were an external collision on the wireless medium. An external collision occurs when more than one AC is granted
Figure 2.17: A simple illustration of a V2I environment of VANET

TXOPs by different nodes. After every unsuccessful transmission, the backoff instant of each ACs enters a new back off procedure and selects a random backoff time from $[0, 2^{j}W[ACx] - 1]$, where $j$ is the number of collision for a specific packet and repeats the above procedure until it reaches the maximum retransmission limit.

2.5 Fairness in Resource Allocation

Fairness is a broad concept of communication systems. Ideally, every node of the network would get the desired service at desired time what they want without disturbing others. However, the real world is not ideal and network congestion does occur, particularly in wireless networks where network capacity has a strict upper limit. When congestion occurs, different nodes might not get what they want, in terms of throughput or delay. The consequence of an unfair resource allocation among different individuals may lead to resource starvation, resource wastage or redundant allocation. The reasons of unfairness problem are unfair allocation of bandwidth, unfair allocation of channel access time, link quality variation, collision of data and different priority of data.
2.5.1 Different forms of fairness definition

Equal opportunity provided to the individuals in resource sharing may not mean equal allocation of resources. On the other hand, a fair allocation may be an outcome of a process where individuals do not have equal opportunity. Therefore, targeted and resultant fairness may not be the same. Fairness can also be considered from the point of view of both, system and individuals. Moreover, individuals of a system may have to carry out various tasks in which case fairness can be defined per task [52]. Thus in this section, we dwell on these concerns and classify the fairness definitions by providing simple but illustrative examples based on the scenario shown in figure 2.17.

2.5.1.1 Targeted and Resultant Fairness

From the point of view of resource allocation and utilization, fairness can be divided into two types: targeted fairness and resultant fairness. Targeted fairness try to achieve fair sharing of resources but resultant fairness aims at fair utilization. Taking figure 2.17 as an example, all vehicles are of the same priority. When each vehicle is assigned the same bandwidth, targeted fairness is achieved. However, if the quality of Link L_2 is worse than that of L_1, it takes longer time for V_2 than V_1 to access the Internet, which means that V_1 and V_2 do not gain the fair access in the view of resultant fairness.

2.5.1.2 Short-term and Long-term Fairness

Considering the time period, fairness can be categorized into short-term and long-term. Short-term fairness focuses on resource allocation in a very short time period. In contrast, long-term fairness measures the resource allocation over a longer time period or at the end of the life cycle. For example in figure 2.17, all vehicles are assumed to have the same priority. Let us say that at 12:00 each node gets 20% of the network capacity, then they reach the short-term fairness at this moment. However, during the previous hour, average capacity of allocation were 10%, 20%, 30%, 5% and 35%, implying that long-term fairness has not been achieved in this period.
2.5.3 System and Individual Fairness

Fairness can be considered both on the system and individual level. The system fairness addresses the overall fairness amongst all individuals in the system, and individual fairness indicates whether a certain individual is treated fairly by the system. For example in figure 2.17, the system fairness of network capacity can be defined as equal allocation (every vehicle gets 20%). However, vehicle $V_1$ can be considered to achieve individual fairness when it gets 20% of the network capacity without the concerns of other vehicles.

2.5.2 Different Forms of Fairness Measurement

Definition of fairness might be different depending on circumstances and preferences. In wireless communication, it is important to know what is perceived as fair in congestion situation varies. It is also important to distinguish what kind of fairness is looked at and how it is measured [53]. Fairness measures are tools to measure fairness level. In section 2.5.3, the most used quantitative/absolute (Jain’s index and entropy) and qualitative/relative (max-min and proportional fairness) fairness measures are described.

2.5.2.1 Quantitative/Absolute Fairness Measure and Qualitative/Relative Fairness Measure

Fairness can be absolute or relative. Absolute fairness means that each node gets the exact same amount of time, throughput or any other desired measure of resources. However, this is often not a very useful measure, since different traffic types have different requirements. Relative fairness is a better way of measuring fairness. Relative fairness takes into account how much of your individual requirements are being fulfilled. The overall relative fairness can be calculated by comparing how much of individual requirements are being fulfilled. Fairness that uses time as a measurement unit is called temporal fairness.

2.5.2.2 Utility Fairness Measure and Cost Fairness Measure

Utility based fairness criteria defines a utility function that describes the utility a node gets from the network with a certain capacity share. It aims to maximize the
total utility of all nodes. Max-min fairness, proportional fairness are special case of utility fairness.

Utility fairness are mostly focused on node rate fairness. In [54], author criticizes this view and says that it is myopic. It is claimed that since schemes based on node rate do not take into account how many nodes create or how long nodes last it would be better to focus on cost fairness. By cost fairness author means sharing out the cost of one node’s actions on others.

2.5.3 Fairness Measurement Schemes

Some notion of fairness is incorporated in many network mechanisms used today. This section presents some well known fairness schemes that are used to measure fairness of the network from different point of view.

2.5.3.1 Jain’s Fairness Index

A well-known index of fairness was proposed by Jain et al. [55]. If the amount of contending nodes is $n$ and $i_{th}$ node receives an allocation $x_i$ then Jain’s fairness index $f(x)$ is

$$f(x) = \frac{\left( \sum_{i=1}^{n} x_i \right)^2}{n \sum_{i=1}^{n} x_i^2}$$

(2.1)

The result is the measure of equality of the allocation of values. The index gets values between 0 and 1. When all the nodes receive an equal share i.e. the system is completely fair, the index gets value 1. Four cases based on the scenario in figure 2.17 are given in table 2.1. As fairness decreases the index value decreases until it reaches 0.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>$V_2$</td>
<td>5%</td>
<td>40%</td>
<td>30%</td>
</tr>
<tr>
<td>$V_3$</td>
<td>30%</td>
<td>50%</td>
<td>30%</td>
</tr>
<tr>
<td>$V_4$</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>$V_5$</td>
<td>65%</td>
<td>0%</td>
<td>20%</td>
</tr>
<tr>
<td>$f(x)$</td>
<td>0.3883</td>
<td>0.4819</td>
<td>0.8333</td>
</tr>
</tbody>
</table>
2.5.3.2 Entropy

Entropy function introduced by Shannon is used as an absolute fairness measure [56]. It is assumed that the proportions of resource are allocated to $n$ vehicles $P = (p_1, p_2, p_3, \ldots, p_n)$ and

$$p_i = \frac{x_i}{\sum_{i=1}^{n} x_i} \quad \text{(2.2)}$$

where, $0 \leq p_i \leq 1$ ($i = 1, 2, 3, \ldots, n)$ and $\sum_{i=1}^{n} p_i = 1$. The uncertainty of the distribution $p$ is called the entropy of the distribution $P$ and is usually measured by $H(p) = H(p_1, p_2, p_3, \ldots, p_n)$ as given below. When $H(p)$ used as a fairness measure, is similar to $f(x)$. Only the absolute resource values of $x$ are replaced by resource proportions $p$.

$$H(p) = \sum_{i=1}^{n} (p_i \log_2 \frac{1}{p_i}) \quad \text{(2.3)}$$

Four cases based on the scenario in figure 2.17 are given in table 2.2. Here, it turns out that entropy is larger when the allocations are fairer.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>1%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>$V_2$</td>
<td>4%</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>$V_3$</td>
<td>30%</td>
<td>50%</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>$V_4$</td>
<td>1%</td>
<td>4%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>$V_5$</td>
<td>64%</td>
<td>1%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>$H(p)$</td>
<td>1.2518</td>
<td>1.4971</td>
<td>2.1710</td>
<td>2.3219</td>
</tr>
</tbody>
</table>

2.5.3.3 Max-min Fairness

A famous fairness scheme in networking is max-min fairness. It means that nodes having small number of packets can fulfill all they demand while nodes having large number of packets have to share the remainder of the capacity equally. Starting from the node having small number of packets, the bandwidth is distributed so that
all nodes receive what they need until bandwidth is exhausted. In the case the nodes that are not receiving all they require, they have to divide the capacity [57].

2.5.3.4 Proportional Fairness

Proportional fairness tries to maintain a balance between maximizing the network throughput and allowing nodes to have at least a minimal level of service. This criterion also favors nodes having small number of packets, but not as much as max-min fairness. A case of proportionally fair scheduling is weighted fair queuing (WFQ) that was introduced by Demers et al. [58]. It aims to ensure that a router’s capacity is fully utilized. Low volume traffic is scheduled first and high volume traffic shares the remaining bandwidth according to weights assigned [59]. In this thesis work, proportional fairness is considered to ensure fair transmission of packet by different velocity vehicles to support both safety and non-safety applications.

2.6 Summary

This chapter gives an overview of WAVE, application of VANET, IEEE 802.11 channel access mechanism and different types of measurement scale of fairness.
Chapter 3

Proposed MAC Protocol for Provisioning Fairness in Vehicle to Infrastructure Communications

3.1 Introduction

VANET is used for both safety and non-safety applications. It contains primarily two types of data: safety applications data and non-safety applications data. Absolute fairness is applicable to the network where same type and same priority data to be transmitted. If all the individual nodes can transmit same amount of data, then absolute fairness is ensured. Relative fairness is applicable to the network where some special conditions would be satisfied. If individual requirements of the nodes are being fulfilled, then relative fairness is ensured. There are two popular relative fairness is: Max-min fairness and proportional fairness. In this research work, proportional fairness is considered. Since VANET has two types of data, absolute fairness is not applicable for VANET. The requirements of the proportional fairness is high velocity vehicles can be transmitted a minimum number of packets to fulfill safety application and other (medium and low velocity) vehicles can be transmitted a certain amount of data which is proportional to the individual residence time. To ensure proportional fairness, dynamic allocation of batch number and dynamic allocation of MAC parameters to the vehicles is performed based on their residence time. Minimum packets transmission of the high velocity vehicles is ensured by setting low minimum contention window size compare with medium and low velocity vehicles. Number of packets transmission is proportional to residence time is ensured by updating batch number dynamically based on residence time. Low velocity vehicles can transmit packet under three batches and medium velocity vehicles can transmit packet under two batches. In this way, number of packets transmission is
proportional to the residence time is achieved by the proposed protocol.

IEEE 802.11p standard [8] is an approved amendment of IEEE 802.11 standard and completely decentralized MAC protocol which is only design to support broadcast in short distance V2V communication [60]. This approach is vulnerable to the hidden terminal problem because it cannot use the request to send (RTS)/clear to send (CTS) for packet broadcasting. Due to absence of acknowledge (ACK), reliable and guaranteed transmission is not properly ensured. Exponential backoff scheme that extends the CW size for decreasing the probability of collision is not used in this protocol [4, 5, 30, 61, 62]. Due to lack of centralized control in V2V, synchronization among vehicles with SI is a difficult task. It is not feasible to select one vehicle as a central access point using a head selection algorithm when vehicles may join or leave the network at a fast rate [63]. In a typical VANET, RSU may offer directly various forms of ITS services to the vehicles using V2I communication [64, 65].

3.2 System Model

In this research work a simple traffic model is considered for vehicles moving along a straight road with both directions covered by one AP or RSU at a fixed position on the road divider, as shown in figure 3.1.

The research work assumes that the vehicles arrive in the network according to a

Figure 3.1: A V2I based VANET model
Poisson process and no transmission error due to defective channel. Each vehicle has two queues: one for safety applications and other for non-safety applications. Two queues are contending independently to access physical medium. The architecture of MAC channel coordination for multichannel operation is shown in figure 3.2. The links between vehicle and RSU both are symmetric and the effect of hidden terminals, exposed terminals and channel capture are ignored. In the coverage area, the vehicles may change the moving direction and velocity. Each vehicle must have capacity to measure its position, moving direction and velocity. The network has three classes of vehicles which are grouped according to residence time.

Figure 3.2: Proposed architecture of IEEE 802.11 DCF MAC channel coordination for multi-channel operation
3.3 Proposed MAC Protocol

The proposed IEEE 802.11 DCF based MAC protocol is a channel access mechanism designed for avoiding unfairness problem at the MAC layer. It defines three class of vehicles in whole network covered by a RSU and denoted by Batch 1, Batch 2 and Batch 3. Each batch vehicles has a queue independently contending for transmission with its own MAC parameters, including minimum contention window ($CW_{\text{min}(i)}$), maximum contention window ($CW_{\text{max}(i)}$), maximum backoff stage ($m_i$) and the retransmission limit value ($m_i + x_i$), where $i$ denote the batch number of the vehicle. In the proposed mechanism, after entering to the network, vehicles will continue the following steps to communicate with RSU.

1. At first every vehicles will associate with the RSU after entering into a particular coverage range of a RSU.

2. Vehicle will compute their velocity, moving direction and position in the network using GPS receiver. After that, vehicles will calculate their residence time in the network. Based on their residence time, vehicles will be associated as a member of Batch $i$.

3. Every vehicle will sense the channel and if the channel is sensed idle until more than or equal to DIFS time then it will enter to the backoff procedure

![Figure 3.3: Channel access mechanism of proposed MAC protocol](image-url)
and execute the steps from 5.

4. If the channel is sensed busy, the vehicle will continue to sense the channel until get idle channel more than or equal to DIFS time. After that vehicle will execute the steps from 5.

5. Every vehicle will check the queue. If the vehicle has at least one packet in the queue, the backoff instant will enter to the backoff procedure. If the vehicle has no packet to transmit, the backoff instant will enter to the post-backoff procedure.

6. In the post-backoff procedure, the backoff instant of the vehicles will start up a backoff counter with the initial value set to one randomly selected from $[0, W_{i,0} - 1]$, where $W_{i,0} = CW_{min(i)}$. After that the vehicles will execute the steps from 8.

7. In the backoff procedure, the backoff instant of the vehicle will start up a backoff counter with the initial value set to one randomly selected from $[0, W_{i,0} - 1]$, where $W_{i,0} = CW_{min(i)}$. After that the vehicles will execute the steps from 8.

8. During the post-backoff procedure, if the channel is sensed busy and the queue becomes empty, the backoff counter will be frozen at the current value. After the channel becomes idle in DIFS time, the backoff counter will be resumed. Then if the channel is sensed idle in a time slot ($\sigma$) and the queue becomes empty, the backoff counter will be decremented by one. When the backoff counter reaches to zero, the queue will wait to receive a packet and after predefined time interval, the vehicles will execute from the steps 2.

9. During the post-backoff procedure, if the channel is sensed busy and the queue has at least one packet to transmit, the backoff instant moves to backoff procedure without change the backoff counter. If the channel is sensed idle and the queue has at least one packet to transmit, the backoff instant moves to backoff procedure with backoff counter will be decremented by one. After that the vehicles continue the next steps.

10. During the backoff procedure, if the channel is sensed busy, the backoff counter will be frozen at the current value and will continue to sense the channel until
get idle channel more than or equal to DIFS time. After the channel becomes idle in DIFS time, the backoff counter will be resumed. Then if the channel is sensed idle in a time slot ($\sigma$), the backoff counter will be decremented by one. When the backoff counter reaches to zero, the packet will be transmitted.

11. If the transmission is successful i.e. transmitting vehicle will receive acknowledgment (ACK) successfully, the vehicle execute the steps from 2.

12. If the vehicle does not receive an ACK packet in a given time, the packet will be retransmitted. At each retransmission, the backoff instant of the vehicle will start up a new backoff counter with the initial value set to one randomly selected from $[0, W_{i,j} - 1]$, where $W_{i,j} = 2^j \times CW_{\min(i)}$ and $j$ is the number of retransmission. After the vehicle execute from the steps 2.

13. If the value of $W_{i,j}$ reaches to $CW_{\max(i)}$, the backoff instant keep the contention window size $CW_{\max(i)}$. Then the vehicle will try to retransmission up to retransmission limit ($m_i + x_i$) without change the contention window size using step 10. After the ($m_i + x_i + 1$) times unsuccessful transmission, the packet will be dropped and vehicle will execute the steps from 2.

14. When the residence time of the vehicle becomes zero, the vehicle will exit from the network and continue the above procedures under the next RSU. The channel access mechanism with batch update procedure is shown in figure 3.3.

### 3.4 Modeling of the Proposed MAC Protocol

#### 3.4.1 Batch Selection

The network model described in figure 3.1 is considered in this research work and at first the batch selection procedure of each vehicles is observed in this section. The instantaneous residence time, $T_r$ of a vehicle can be expressed as

$$T_r = \frac{R \pm r}{v}$$

(3.1)

where, $R$ is the radius of the coverage range of RSU, $r$ is the instantaneous distance of a vehicle from RSU, $v$ is the instantaneous velocity of a vehicle, ‘$\pm$’
indicates the moving direction of vehicle toward to RSU and '-' indicates the moving direction of vehicle backward from RSU.

Let, the velocity of the vehicles is uniformly distributed in \([v_{\text{min}}, v_{\text{max}}] \text{ms}^{-1}\).

Different residence time of the vehicles are computed as

\[
T_{r(\text{min})} = \frac{2R}{v_{\text{max}}} \quad (3.2)
\]

\[
T_{r(\text{max})} = \frac{2R}{v_{\text{min}}} \quad (3.3)
\]

\[
T_{r(\text{in})} = \frac{T_{r(\text{min})} + T_{r(\text{max})}}{2} \quad (3.4)
\]

where, \(T_{r(\text{min})}\), \(T_{r(\text{in})}\) and \(T_{r(\text{max})}\) are minimum residence time, intermediate residence time and maximum residence time respectively. Selection of batch of the vehicles can be occurred by the table 3.1 after passing certain time interval.

<table>
<thead>
<tr>
<th>Instantaneous Residence Time ((T_r))</th>
<th>Batch No ((B_i))</th>
<th>Maximum Residence Time ((T_{r(i)}))</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (&lt; T_r \leq T_{r(\text{min})})</td>
<td>(B_1)</td>
<td>(T_{r(\text{min})})</td>
<td>High</td>
</tr>
<tr>
<td>(T_{r(\text{min})} ,&lt; T_r \leq T_{r(\text{in})})</td>
<td>(B_2)</td>
<td>(T_{r(\text{in})})</td>
<td>Medium</td>
</tr>
<tr>
<td>(T_{r(\text{in})} ,&lt; T_r \leq T_{r(\text{max})})</td>
<td>(B_3)</td>
<td>(T_{r(\text{max})})</td>
<td>Low</td>
</tr>
</tbody>
</table>

According to E. Karamad et al. [10], the packet transmission rate, \(R_i\) of a vehicle in batch \(i\) \((i = 1, 2, 3)\) can be expressed as

\[
R_i = H \frac{R_{\text{bit}}}{N_{\text{bit}}} \frac{P_{t(i)}}{\sum_{k=1}^{3} P_{t(k)}} \quad (3.5)
\]

where, \(H\) is the normalized throughput of the network, \(N_{\text{bit}}\) is the average number of bits in the packet, \(R_{\text{bit}}\) is the bit rate over the channel and \(P_{t(i)}\) is the transmission probability of the vehicle in batch \(i\).

To avoid unfairness by ensuring minimum access, the total number of packets transmitted within the average residence time of vehicle of each batch in the network is equal to \(N_P\). Thus \(N_P\) can be written as

\[
R_i T_{r(i)} = N_P \quad (3.6)
\]

Where, \(N_P\) is the minimum number of packet transmitted by every vehicle to ensure proportional fairness.
3.4.2 Markov Chain Analysis

At first a 2-D Markov chain is constructed to describe the post-backoff procedure and backoff procedure of vehicle queue for non-saturated and saturated state respectively, which is shown in figure 3.4. In this Markov chain, the state of each vehicle queue is denoted by \((i, j, k)\), where \(i\) is just an index standing for the batch number, \(j\) is the backoff stage number and \(k\) is the value of backoff counter. The backoff stage, \(j\), starts at 0 at the first attempt to transmit a packet and is increased by one every time a transmission attempts results in a collision, up to a maximum value \(m_i + x_i\). It is reset to either 0 or \(e\) after a successful transmission or a packet drop for representing the queue is non-empty or empty respectively. The value of \(k\) is initially set to one that is uniformly selected from \([0, W_{i,j} - 1]\) once a state reaches stage \(j\) and is either decremented by one if the channel is sensed idle in a slot or frozen if a transmission is detected on the channel, and reactivated when the channel is sensed idle again more than a DIFS time. Transmission is attempted when channel is sensed idle for DIFS time after backoff counter reached to zero.

The contention window of a vehicle of batch \(i\) at the stage \(j\) is defined by

\[
W_{i,j} = \begin{cases} 
CW_{\text{min}(i)} ; & j = 0 \text{ or } e \\
2^{j}CW_{\text{min}(i)} ; & 1 = j \leq m_i \\
CW_{\text{max}(i)} ; & m_i \leq j \leq m_i + x_i
\end{cases}
\]  

(3.7)

At the time of backoff procedure, if the channel is sensed busy, the backoff counter is frozen to the present backoff value and if the channel is sensed idle, the backoff counter is decremented by one. For \(0 < k = W_{i,j} - 1\), these one-step transition probabilities are given by

\[
P_{i,j,k \mid i,j,k} = 1 - P_{\text{idle}(i)} ; \quad 0 \leq j \leq m_i + x_i
\]  

\[P_{i,j,k-1 \mid i,j,k} = P_{\text{idle}(i)} ; \quad 0 \leq j \leq m_i + x_i
\]  

(3.8)

(3.9)

During the backoff procedure, after each unsuccessful transmission attempt, the backoff instance moves down to below row at probability \(P_{\text{coll}(i)}\) until reaches to maximum retransmission limit \(m_i + x_i\) and chose a random backoff time at probability \(1/W_{i,j}\). For \(0 < k \leq W_{i,j} - 1\) and \(0 \leq j \leq m_i + x_i - 1\), this one-step transition
Figure 3.4: Markov chain model for the backoff procedure of a vehicle with both saturated and non-saturated state.
The probability is given by

\[
P_{i,j+1,k \mid i,j,0} = \frac{P_{\text{coll}(i)}}{W_{i,j}}
\]  

(3.10)

After exceeding the retransmission limit, the packet is dropped at probability \( P_{\text{drop}(i)} \).

\[
P_{\text{drop}(i)} = P_{\text{coll}(i)}^{m_i + x_i + 1}
\]  

(3.11)

During the backoff procedure, after each successful transmission or packet drop, the backoff instance moves to second row at probability \( P_{\text{succ}(i)} \) or \( P_{\text{drop}(i)} \) respectively if there is a packet waiting in the transmission queue represented by probability \( 1 - P_{\text{eqat}(i)} \) or moves of first row if there is no packet waiting in the transmission queue represented by the probability \( P_{\text{eqat}(i)} \) and backoff instance enters to the post-backoff procedure. When backoff instance reaches to the state \((i, j, 0)\) of Markov chain, the channel idle probability is zero. So that the probability of successful transmission is \( 1 - P_{\text{coll}(i)} \). For \( 0 \leq k \leq W_{i,0} - 1 \), these one-step transition probabilities are given by

\[
P_{i,e,k \mid i,j,0} = \frac{(1 - P_{\text{coll}(i)}) P_{\text{eqat}(i)}}{W_{i,0}} \quad ; \quad 0 \leq j \leq m_i + x_i - 1
\]  

(3.12)

\[
P_{i,0,k \mid i,j,0} = \frac{(1 - P_{\text{coll}(i)}) (1 - P_{\text{eqat}(i)})}{W_{i,0}} \quad ; \quad 0 \leq j \leq m_i + x_i - 1
\]  

(3.13)

\[
P_{i,e,k \mid i,m_i + x_i,0} = \frac{P_{\text{eqat}(i)}}{W_{i,0}}
\]  

(3.14)

\[
P_{i,0,k \mid i,m_i + x_i,0} = \frac{1 - P_{\text{eqat}(i)}}{W_{i,0}}
\]  

(3.15)

During the post-backoff procedure, if the channel is sensed idle and the queue is empty, the backoff counter is decremented by one, if the channel is sensed idle and the queue has at least one packet to transmit, the backoff counter is decrement by one and backoff instance jump to next backoff stage, if the channel is sensed busy and the queue is empty, the backoff counter is frozen, or if the channel is sensed busy and the queue has at least one packet to transmit, the backoff counter is frozen and backoff instance jump to next backoff stage. For \( 0 < k \leq W_{i,0} - 1 \), these one-step transition probabilities are given by

\[
P_{i,e,k \mid i,e,k} = P_{\text{eq}(i)} (1 - P_{\text{idle}(i)})
\]  

(3.16)

\[
P_{i,e,k-1 \mid i,e,k} = P_{\text{eq}(i)} P_{\text{idle}(i)}
\]  

(3.17)

\[
P_{i,0,k-1 \mid i,e,k} = (1 - P_{\text{eq}(i)}) P_{\text{idle}(i)}
\]  

(3.18)
\[ P_{i,0,k \mid \text{e},i,k} = (1 - P_{eq(i)}) (1 - P_{idle(i)}) \] (3.19)

When back-off instance complete the post back-off procedure then it is waiting for a packet at probability \( P_{eq(i)} \). If it receives a packet and channel is busy, the back-off instance shift down to next back-off stage but when channel is sensed idle and received a packet, the backoff instance moves to state \((i,0,0)\) to attempt transmission.

\[ P_{i,0,0 \mid \text{e},i,0} = P_{eq(i)} \] (3.20)

\[ P_{i,0,0 \mid \text{e},i,0} = (1 - P_{eq(i)}) P_{idle(i)} \] (3.21)

\[ P_{i,0,k \mid \text{e},i,0} = \frac{(1 - P_{eq(i)}) (1 - P_{idle(i)})}{W_{i,0}} ; \quad 0 \leq k \leq W_{i,0} - 1 \] (3.22)

Let, \( a = \sum_{j=0}^{m_i+x_i-1} P_{\text{suc}(i)} b_{i,j,0} + b_{i,m_i+x_i,0} \) and \( b = a (1 - P_{eq(i)}) + (1 - P_{idle(i)}) (1 - P_{eq(i)}) b_{i,e,0} \)

According to the 2-D Markov chain in figure 3.4, all birth-death equations write recursively through the chain from upper row to lower row and from right to left, then the following stationary probabilities are given as follows:

\[ b_{i,e,0} = \frac{a P_{eq(i)} 1 - P_{eq(i)}^{W_{i,0}}}{W_{i,0} (1 - P_{eq(i)}) (1 - P_{eq(i)})} \] (3.23)

\[ b_{i,0,k} = \frac{b(W_{i,0} - k)}{W_{i,0} P_{idle(i)}} + (1 - P_{eq(i)}) P_{idle(i)} b_{i,e,k+1} \]

\[ + (1 - P_{eq(i)}) (1 - P_{idle(i)}) b_{i,e,k} ; \quad 0 < k \leq W_{i,0} - 1 \] (3.24)

\[ b_{i,j,k} = \frac{W_{i,j} - k}{W_{i,j} P_{idle(i)}} P_{\text{coll}(i)}^{j} b_{i,0,0} ; \quad 0 < j \leq m_i + x_i \] (3.25)

\[ b_{i,j,o} = P_{\text{coll}(i)}^{j} b_{i,0,0} ; \quad 0 \leq j \leq m_i + x_i \quad \text{and} \quad 0 < k \leq W_{i,0} - 1 \] (3.26)

Using the above equations, all stationary probabilities \( b_{i,j,k} \) are expressed by \( b_{i,0,0} \) and which is finally determined by imposing the normalization condition, as follows:

\[ \sum_{k=0}^{W_{i,0} - 1} b_{i,e,k} + \sum_{j=0}^{m_i+x_i} \sum_{k=0}^{W_{i,j} - 1} b_{i,j,k} = 1 \] (3.27)
\[ \Rightarrow b_{i,e,0} + \sum_{k=1}^{W_{i,0}-1} b_{i,e,k} + b_{i,0,0} + \sum_{j=1}^{m_i} b_{i,j,0} + \sum_{k=1}^{W_{i,0}-1} b_{i,0,k} + \sum_{j=1}^{m_i+x_i} \sum_{k=1}^{W_{i,j}-1} b_{i,j,k} = 1 \]

\[ \Rightarrow \frac{1}{b_{i,0,0}} = 1 + \frac{(1 - P_{\text{eqat}(i)}) (W_{i,0} - 1)}{2P_{\text{idle}(i)}} + \sum_{j=1}^{m_i+x_i} P_{\text{coll}(i)}^j \left( \frac{W_{i,j}}{1 - P_{\text{eq}(i)}} \right) \left( \frac{1 - P_{\text{coll}(i)}}{2P_{\text{idle}(i)}} \left( \frac{2P_{\text{eq}(i)}}{1 - P_{\text{eq}(i)}} + (W_{i,0} - 1) \right) - \frac{1}{P_{\text{eq}(i)}} \right) + \frac{P_{\text{eqat}(i)}}{W_{i,0}} \left( \frac{2(2 - P_{\text{eq}(i)})}{P_{\text{idle}} (1 - P_{\text{eq}(i)})} + \frac{1 - P_{\text{eq}(i)}}{P_{\text{eq}(i)}} \right) \]

(3.28)

Packet transmission occurs if backoff counter becomes zero, regardless of the backoff stage. So packet transmission probability of a vehicle in a random time slot express as:

\[ P_t(i) = b_{i,0,0} \frac{1 - P_{\text{coll}(i)}^{m_i+x_i+1}}{1 - P_{\text{coll}(i)}} \]  

(3.29)

Substituting equation 3.28 and 3.29, the packet transmission probability of a vehicle in a randomly chosen time slot is produced.

### 3.4.3 Throughput Analysis

However, \( P_{t(i)} \) depends on the conditional collision probability, \( P_{\text{coll}(i)} \) and channel idle probability, \( P_{\text{idle}(i)} \), Which is still unknown. A vehicle of a batch \( i \) is sensed idle channel if there is no other vehicle of batch \( i \) and other batch transmits simultaneously in the channel. A successful transmission occurs if only one vehicle transmits packet in a time slot and collision occurs when more than one vehicle transmits packet in a time slot. According to Y. H. Bae et al. [16], \( P_{\text{idle}(i)} \), \( P_{\text{succ}(i)} \) and \( P_{\text{coll}(i)} \) can be calculated as follows:

\[ P_{\text{idle}(i)} = \prod_{i=1}^{3} (1 - P_{t(i)})^{n_i} \]  

(3.30)

\[ P_{\text{succ}(i)} = \sum_{i=1}^{3} n_i P_{t(i)} \prod_{i=1}^{3} (1 - P_{t(i)})^{n_i} \]  

(3.31)

\[ P_{\text{coll}(i)} = 1 - \sum_{i=1}^{3} \prod_{k=1}^{n_i} (1 - P_{t(k)})^{n_k} - \prod_{i=1}^{3} (1 - P_{t(i)})^{n_i} \]  

(3.32)
According to Bianchi model [35], the throughput of batch $i$ of the network can be calculated as:

$$S_i = \frac{T_p P_{\text{succ}(i)}}{T_{\text{succ}} P_{\text{succ}(i)} + T_{\text{coll}} P_{\text{coll}(i)} + \sigma P_{\text{idle}(i)}}$$  \hspace{1cm} (3.33)

Where, $T_p$ is the average packet length in time, $\sigma$ is the time duration of an empty slot, $T_{\text{coll}}$ is the average time containing two or more colliding packet and $T_{\text{succ}}$ is the average time containing a successfully transmitted packet.

Time intervals $T_{\text{succ}}$ and $T_{\text{coll}}$ depend on the access method used. In the case of the basic access method they are as follows.

$$T_{\text{succ}} = T_{\text{DIFS}} + T_H + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}} + 2\delta$$  \hspace{1cm} (3.34)

$$T_{\text{coll}} = T_{\text{DIFS}} + T_H + T_{\text{DATA}} + T_{\text{ACK(timeout)}} + \delta$$  \hspace{1cm} (3.35)

where $T_{\text{ACK(timeout)}}$ is assumed to be $T_{\text{EIFS}} - T_{\text{DIFS}}$.

In the case of RTS/CTS access mechanism they are as follows.

$$T_{\text{succ}} = T_{\text{DIFS}} + T_{\text{RTS}} + T_{\text{SIFS}} + T_{\text{CTS}} + T_H + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}} + 4\delta$$  \hspace{1cm} (3.36)

$$T_{\text{coll}} = T_{\text{DIFS}} + T_{\text{RTS}} + T_{\text{CTS(timeout)}} + \delta$$  \hspace{1cm} (3.37)

Where $\delta$ denotes the propagation delay and $T_H$ is the time required to send the PHY and MAC headers. The $T_{\text{CTS(timeout)}}$ is assumed to be $T_{\text{EIFS}} - T_{\text{DIFS}}$.

### 3.5 Summary

This chapter presents an efficient MAC protocol to ensure the proportional fairness of V2I network environment of VANET. The proposed protocol introduces a novel scheme to search a minimum contention window size for provisioning proportional fairness and a dynamic batch selection method based on the residence time.

Also a Markov Model is developed to mathematically analyze the proposed protocol for validation of the network performances in terms of throughput of the network.
Chapter 4

Results and Performance Evaluation

4.1 Introduction

In order to validate the proposal and verify its mathematical model MATLAB simulation tool is used. The MATLAB tool is very popular and efficient to verify mathematical models. The proposed protocol is analyzed through a mathematical model and by using MATLAB the developed equations are solved using this tool. All the equations from the Markov Model are used in the MATLAB editor and solved them to plot different results for the proposed protocol.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p(\mu s)$</td>
<td>8184</td>
<td>$H$</td>
<td>0.8</td>
</tr>
<tr>
<td>$T_{succ}(\mu s)$</td>
<td>8972</td>
<td>$R_{bit}(Mbps)$</td>
<td>1</td>
</tr>
<tr>
<td>$T_{coll}(\mu s)$</td>
<td>8713</td>
<td>$N_{bit}(byte)$</td>
<td>216</td>
</tr>
<tr>
<td>$\sigma(\mu s)$</td>
<td>50</td>
<td>$D(m)$</td>
<td>500</td>
</tr>
<tr>
<td>$SIFS(\mu s)$</td>
<td>28</td>
<td>$N_P$</td>
<td>4000</td>
</tr>
<tr>
<td>$DIFS(\mu s)$</td>
<td>128</td>
<td>$v_{max}(ms^{-1})$</td>
<td>45</td>
</tr>
<tr>
<td>$ACK(\mu s)$</td>
<td>240</td>
<td>$v_{min}(ms^{-1})$</td>
<td>5</td>
</tr>
</tbody>
</table>

4.2 Analytical Results

The performance analysis of the proposed MAC protocol based on the analytical model is carried out in this section. For simplicity, the research work assumes that all types of vehicles transmit packets of equal lengths (216 bytes) and probabilities (0.01) that a queue has packets waiting for transmission are equal and use basic
Figure 4.1: Selection of minimum contention window size based on transmission probability

access mechanism. The parameters used in the analytical experiments are listed in table 4.1.

4.2.1 Selection of Minimum Contention Window Size

Figure 4.1 shows the relationship between the transmission probability of the vehicle and the minimum contention window size. It is seen that minimum contention window size increases as the transmission probability decreases. To ensure fairness, the transmission probability of each batch is calculated by using equation 3.5 and

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CW_{min} )</td>
<td>3</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>( CW_{max} )</td>
<td>12</td>
<td>112</td>
<td>1280</td>
</tr>
<tr>
<td>( m_i )</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>( x_i )</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
3.6. The calculated transmission probability is used to determine the minimum contention window size of each batch for further analysis and the output from the figure 4.1 describes it as well. The maximum backoff stage and retransmission limit of each batch is set a fixed value for simplicity. The minimum and maximum contention window size and retransmission limit of each batch is summarized in table 4.2.

4.2.2 Comparison of Different Probabilities of Different Batches

4.2.2.1 Channel Idle Probability

The channel idle probability of each batch under the increasing number of vehicles in the network is shown in figure 4.2. The channel idle probability is decreases as the number of vehicles increases for each batches. This is because as the number of vehicles increases, more vehicles would contend for transmission in the same time slot, resulting decrement of channel idle probability. Due to low contention window size of high priority batch (Batch 1) compared to other batches (Batch 2 and Batch 3), the density of vehicles in a backoff stage is high for same number of vehicles,
resulting in low probability of channel being idle. For Batch 1 when the number of vehicles is less than 2, then the channel idle probability is maximum and is above 90%. This is because less vehicles tends to less contention and as a result the network remains idle for long time. But when the number of vehicles increases, for example 20 vehicles in the network causes channel idleness less than 45%. And this percentage becomes more less for increasing number of vehicles. For other two batches Batch 2 and Batch 3 this probability starts from less than 80% and 75% respectively. For Batch 2 and Batch 3 this probability remains almost same under varying number of nodes because of high contention window size.

### 4.2.2.2 Collision Probability

Figure 4.3 shows the probability of collision of each batch under different number of vehicles in the network. From the figure 4.3 it can be seen that the probability of collision of Batch 1 increases as the number of vehicles in the network increases. When there are less number of vehicles the collision probability is less than 10% for Batch 1 and the probability increases up to 22% as the number of vehicles increases. Because more number of vehicles results more attempt to contention and
occurs more collision for Batch 1 as the contention window of Batch 1 vehicles is minimum as compared to the other batches. Due to low contention window size of high priority batch compared to other batches, high priority batch will get more chance to transmit packet and thus will suffer less collision for low density vehicles. For high density network, high priority batch would got more collision compared to other batches. The collision probability for Batch 2 and Batch 3 is 22% and 27% respectively at the initial state of the network.

4.2.2.3 Successful Transmission Probability

The probability of successful transmission of each batch under different number of vehicles in the network is shown in figure 4.4. The probability of successful transmission increases proportionally with the increasing number of vehicles. The successful transmission probability of Batch 1 is much greater than other two batches Batch 2 and Batch 3. For Batch 1 this probability is up to 35% or more under varying number of nodes. For Batch 2 the successful transmission probability is less compared to Batch 1, because the contention window (CW) for Batch 1 is selected minimum to give high priority to this batch vehicle than the other batches. For

![Figure 4.4: Probability of successful transmission vs number of vehicle](image-url)
Batch 3 vehicle the CW is maximum compared to Batch 1 and Batch 2, that’s why the successful transmission probability of Batch 3 is minimum and is less than 5%. This is because Batch 3 vehicles get more time to access the network and when these vehicles enters to the high priority batches the successful transmission probability increases also.

4.2.2.4 Packet Drop Probability

Figure 4.5 shows the probability of packet drop of each batch under different number of vehicles in the network. This probability increases for each batch with the number of increasing vehicles. The packet drop probability is very low for Batch 1 vehicles and is almost zero percent when the network has minimum number of vehicles. The probability increases when the network is populated with vehicles and the contention increases among vehicles greatly. The packet drop probability of Batch 2 and Batch 3 is higher compared to Batch 1 at the initial state of the network. When the network is densely populated the packet drop probability of all batch vehicles performance is almost same.

![Figure 4.5: Probability of packet drop vs number of vehicle](image)

Figure 4.5: Probability of packet drop vs number of vehicle
Transmission probability is the probability that the vehicles get the opportunity to transmit its packets. The transmission probability of Batch 1 vehicles is better than other batches Batch 2 and Batch 3. It is also seen from the figure 4.6 that the transmission probability of Batch 1 is greater than other batches. This is because Batch 1 vehicles have the high priority to access the network first and this is done by giving them minimum CW for contention. Batch 2 and Batch 3 vehicles have greater CW compared to Batch. Batch 2 vehicles occupied the channel for long period of times than Batch 1 and less than batch 3 vehicles. Batch 1 vehicles get short period of time to access the network that’s why the transmission probability of these batch vehicles are maximum than other batches and Figure 4.6 shows the same.
4.2.3 Non-saturated Normalized Throughput Evaluation

4.2.3.1 Throughput of Different Batches

Figure 4.7 shows the throughput of each batch vehicles with respect to the increasing number of vehicles in the network. Throughput of each batch reaches a maximum value with the increasing number of varying vehicles. The throughput for Batch 1 is close to 60% as compared to the other batches; this is because the small number of vehicles leads to a low throughput for each vehicle. With the number of vehicles increasing within a certain range, it may not cause many collisions, resulting in an increase of the throughput for each batch vehicles. With the further increase in the number of vehicles, however, more vehicles will arrive in the network and will contend for transmission simultaneously, which would result in more collisions and thus a reduction in the throughput for each batch vehicle. For Batch 2 and Batch 3 the throughput is close to 30% and 10% respectively.

Figure 4.7: Throughput vs number of vehicle
Table 4.3: Batch selection

<table>
<thead>
<tr>
<th>Instantaneous Residence Time (sec) ( (T_r) )</th>
<th>Batch No ( (B_i) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 &lt; T_r \leq 11.11 )</td>
<td>( B_1 )</td>
</tr>
<tr>
<td>( 11.11 &lt; T_r \leq 55.55 )</td>
<td>( B_2 )</td>
</tr>
<tr>
<td>( 55.55 &lt; T_r \leq 100 )</td>
<td>( B_3 )</td>
</tr>
</tbody>
</table>

4.2.3.2 Total Throughput of Vehicle

Figure 4.8 shows the total normalized throughput of vehicles with respect to the increasing number of vehicles in the network. It is assumed that initially three types of vehicles enter in the network with having velocities \( 5 \, ms^{-1} \), \( 9 \, ms^{-1} \) and \( 45 \, ms^{-1} \) and this is unchanged to the whole residence time. According to the batch selection table 4.3, first type vehicles enter to the network as a member of Batch 3, second type vehicles as a member of Batch 2 and last type vehicle as a member of Batch 1. It is observed that in figure 4.8, the vehicles which are entered to the network as a member of Batch 3, achieve highest throughput because this vehicles get three times (as a member of Batch 3, Batch 2 and Batch 1) chance to transmit data. The
Figure 4.9: Number of transmitted packets vs residence time

vehicles which are entered to the network as a member of Batch 2, achieve second highest throughput because this vehicles get two times (as a member of Batch 2 and Batch 1) chance to transmit data. The vehicles which are entered to the network as a member of Batch 1, achieve lowest throughput because it have no chance to enter other batches. It is clear that throughput is proportional to the residence time of the vehicles.

4.2.4 Maximum Transmitted Data of Different Protocols

Figure 4.9 shows the comparison of maximum number of transmitted packets of different MAC protocols with various velocities under residence time. It is observed that in IEEE 802.11 DCF MAC, variation in data transmission amount between high and low velocity vehicles increases with velocity increment without ensuring a minimum access for high velocity vehicles. For karamad protocol [66], the amount of packet transmission is constant regardless of velocity variation. However, in this research work the proposed protocol clearly demonstrates that the number of packets transmission remain proportional to the residence time as well as a minimum channel access for high velocity vehicles is ensured. The proposed protocol also ensures that
Figure 4.10: Maximum number of packet transmission vs different proposed protocols with considering different velocities

the fairness for all kind of vehicles under different batches.

4.2.5 Effect of Velocity on Packet Transmission

Figure 4.10 shows the amount of maximum transmitted data (packet) under different MAC protocols. It is seen that IEEE 802.11 DCF MAC protocol offers a maximum transmitted data which is proportional to the residence time of the vehicles because a common MAC parameter is used by all the vehicles. Moreover, Karamad proposed MAC protocol [66] offers an equal maximum transmitted data regardless of residence time because each batch vehicles use different MAC parameters which are determined by considering total number of packets transmitted within the residence time of each batch in the network should be equal.

4.3 Summary

This chapter presents the graphical representation of the proposed protocol and compare with different protocols. The proposed protocol ensure the proportional fairness i.e. all vehicles must transmit a minimum number of packets and amount of maximum transmitted data is proportional to their residence time. The proposed protocol ensures better fairness than IEEE 802.11 DCF and Karamad’s protocol compared with number of maximum transmitted data.
Chapter 5

Conclusion and Future Work

5.1 Conclusion

In vehicular ad-hoc networks, unfairness problem arises due to the varying residence time of the vehicles. In this thesis work considering this problem, an efficient MAC protocol based on 802.11 DCF is proposed which adapts the MAC parameters of each vehicle according to its residence time and updates the MAC parameters after certain time interval. Every vehicle has the chance to adapt at least higher priority MAC parameters. As a result, fairness in the sense of minimum chance of communicating with RSU for the vehicles having minimum residence time and time proportional chance of communicating with RSU for the other vehicles is achieved. Furthermore, An analytical models is developed to analyze the performance of the proposed MAC protocol in a non-saturated state taking into account all major factors that could affect the access performance of the proposed MAC protocol, including the saturation condition, backoff counter freezing, channel idle, collision, successful transmission, packet drop and retransmission limit. Based on the analytical model, relation between the transmission probability and minimum contention window size, and the relationship between number of vehicles and some other important parameters including probability of collision, probability of packet drop, probability of channel idle, probability of successful transmission, probability of transmission and throughput is derived. Moreover, it is shown that the value of MAC parameters can be determined for a given velocity in order to achieve fair access. Finally, the relationship between maximum transmitted data and residence time of the vehicles to compare the performance of the proposed MAC protocol with basic access mechanism IEEE 802.11 DCF MAC and E. Karamad MAC protocol is
explored. Accordingly, the proposed MAC protocol overcomes the unfairness problem by ensuring minimum access of all the vehicles for both safety and non-safety applications.

5.2 Future Work

The proposed protocol ensures the proportional fairness of V2I communication without QoS. In future the research work will be proposed a MAC protocol to ensuring proportional fairness for V2V and V2I communication with QoS and the performance is analyzed by both analytical model and simulation environment.
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