**UNIVERSITI PUTRA MALAYSIA**

# CHANNEL CONGESTION CONTROL MECHANISMS FOR IEEE 802.11P/1609.4 IN VEHICULAR AD-HOC NETWORKS

**AKRAM ABDULLAH AL-ZAGHIR**

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By

**AKRAM ABDULLAH ALI AL-ZAGHIR**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

**July 2019**

# DEDICATION

This thesis is dedicated to

All those I love

Especially

My dearest parents

My uncle Nabil

My wife Nor Aidillina

My little girl Nor Alaa

My brothers and sisters

For their endless encouragement, patience, and support and for being a great source of motivation and inspiration

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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**July 2019**

**Chairman : Professor Nor Kamariah bt. Noordin, PhD**
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Vehicular ad-hoc networks (VANETs) are a kind of wireless network which has been developed to provide safety-related and commercial service applications on the road. The IEEE 802.11p/1609.4 is a standard protocol designed to support multi-channel operation in VANETs in order to enable the transmission of safety and service applications in different channels. However, the existing analytical models for IEEE 802.11p/1609.4 in VANETs assume that the wireless channel is error-free. Such assumption is inaccurate, especially when dealing with a decentralized wireless network as in VANETs. Moreover, due to the nature of contention-based channel access scheme and the transmission of multiple applications over the CCH sharing a common radio frequency, the safety applications performance is degraded during CCH congestion in high network density scenarios. Therefore, CCH congestion is the major issue encountered while providing Quality of Service (QoS) over VANETs. The first goal of this research is to design analytical models of IEEE 802.11p/1609.4 in VANETs for safety and service application based on Markov chain in the presence of the error-prone channels. The second goal is to develop efficient and reliable channel congestion control mechanisms for IEEE 802.11p/1609.4 in VANETs. To do so, this thesis proposes an Adaptive Multi-Channel Assignment and Coordination (AMAC) scheme for the IEEE 802.11p/1609.4 in VANETs. AMAC scheme initially calculates the Control Channel Busy Ratio (CCBR). Based on the CCBR value, the AMAC scheme performs three functions. First, AMAC scheme decides which channel access scheme should be used in every synchronization interval (SI). Second, AMAC scheme performs an adaptive Peer-to-Peer Negotiation Phase (PNP) mechanism between service providers and users for SCH resource reservations. Thus, the P2P mechanism will be executed either over CCH or SCHs according to the CCH conditions. Lastly, AMAC scheme estimates appropriate contention window sizes values to be used by the vehicles, this approach is called collision-aware packet transmission mechanism. Employing these mechanisms result in higher QoS for different traffic flows over VANETs. The proposed mechanisms are numerically analyzed and then simulated

using MATLAB and Network Simulator 2, respectively. For comparison purpose, two existing schemes are considered. One scheme, called Analytical Study of the IEEE 1609.4 MAC in Vehicular Ad Hoc Networks (AS-MAC), is used to compare with the proposed analytical model. The second scheme, called Efficient and Reliable MAC protocol for VANETs (VER-MAC), is used to compare with the proposed AMAC scheme. The numerical and simulation results demonstrate that the proposed analytical model and AMAC scheme outperform the existing AS-MAC model and VER-MAC scheme in terms of five performance metrics studied. These metrics include collision probability, average delay, and packet delivery ratio of safety packets, as well as WSA packets drop probability and system throughput of service packets. For instance, under various vehicles numbers, the results of the proposed AMAC scheme show improvement by 97.90%, 40.79%, 15.27%, 94.23%, and 105.72% for the five-performance metrics compared to the VER-MAC scheme, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**MEKANISMA KAWALAN KESESAKAN SALURAN UNTUK IEEE 802.11P/1609.4 DALAM RANGKAIAN AD-HOV KENDERAAN**

Oleh

**AKRAM ABDULLAH ALI AL-ZAGHIR**

**Julai 2019**

**Pengerusi : Profesor Nor Kamariah bt. Noordin, PhD**
**Fakulti : Kejuruteraan**

Rangkaian ad-hoc kenderaan (VANETs) adalah sejenis rangkaian tanpa wayar yang telah dibangunkan untuk menyediakan aplikasi perkhidmatan berkaitan keselamatan dan pengkomersialan di jalan raya. IEEE 802.11p / 1609.4 adalah protokol standard yang direka untuk menyokong operasi pelbagai saluran di VANET bagi membolehkan penghantaran aplikasi keselamatan dan perkhidmatan dalam saluran yang berbeza. Model analisis sedia ada IEEE 802.11p / 1609.4 dalam VANET mengandaikan bahawa saluran tanpa wayar bebas daripada ralat. Walau bagaimanapun, anggapan tersebut tidak tepat, terutamanya apabila menggunakan rangkaian berpusat tanpa wayar seperti VANETs. Selain itu, skim capaian saluran berasaskan ketidaksepadanan dan penghantaran pelbagai aplikasi ke atas CCH berkongsi frekuensi radio yang sama, maka prestasi aplikasi keselamatan merosot ketika kesesakan CCH dalam senario kepadatan rangkaian yang tinggi. Oleh itu, kesesakan CCH adalah isu utama yang dihadapi semasa menyediakan Kualiti Perkhidmatan (QoS) ke atas VANETs. Tujuan kajian ini adalah untuk merekabentuk model analisis IEEE 802.11p / 1609.4 dalam VANETs untuk aplikasi keselamatan dan perkhidmatan berdasarkan rantaian Markov dengan kehadiran saluran rawan kesalahan serta membangunkan mekanisme kawalan kesesakan saluran yang cekap dan boleh dipercayai untuk IEEE 802.11p / 1609.4 dalam VANETs. Oleh itu, kajian ini mencadangkan skim Penyeragaman dan Pelarasan Multi-Saluran Penyelarasan (AMAC) untuk IEEE 802.11p / 1609.4 dalam VANETs. Berdasarkan nilai CCBR, skim AMAC melaksanakan tiga fungsi. Pertama, skema AMAC menentukan saluran akses yang mana harus digunakan dalam setiap selang penyelarasan (SI). Kedua, skim AMAC melaksanakan mekanisme Tahap Perundingan *Peer-to-Peer-Peer* (PNP) adaptif antara penyedia perkhidmatan dan pengguna untuk reservasi sumber SCH. Akhir sekali, skema AMAC menganggarkan nilai-nilai saiz tetingkap yang sesuai untuk digunakan oleh kenderaan, pendekatan ini dipanggil mekanisma transmisi paket pelanggaran. Mekanisme yang dicadangkan dianalisis secara numerik dan disimulasikan menggunakan MATLAB dan Network Simulator 2. Untuk tujuan perbandingan, dua skim sedia ada dipertimbangkan. Satu

skim adalah Kajian Analisis MAC IEEE 1609.4 dalam Rangkaian Ad Hoc Kenderaan dan skim kedua adalah protokol MAC untuk VANETs (VER-MAC). Keputusan yang diperoleh menunjukkan bahawa model analisis yang dicadangkan dan skema AMAC telah mengatasi model AS-MAC sedia ada dan skema VER-MAC dari lima aspek metrik prestasi yang dikaji iaitu kebarangkalian perlanggaran, kelewatan purata, nisbah penghantaran paket keselamatan, kebarangkalian kejatuhan paket WSA dan sistem penghantaran paket perkhidmatan. Keputusan skim AMAC yang dicadangkan menunjukkan peningkatan iaitu 97.90%, 40.79%, 15.27%, 94.23% dan 105.72% bagi lima metrik prestasi berbanding skim VER-MAC.

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Last but not least, I acknowledge my sincere indebtedness and gratitude to my loving wife and my sweet daughter for their love, sacrifice and lifting my spirits through this period.

**Declaration by graduate student**

I hereby confirm that:

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| | |
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| | |
|---|---|
| VANETs | Vehicular ad-hoc networks |
| CCH | Control Channel |
| SCHs | Service Channels |
| WSAs | WAVE Service Announcements |
| QoS | Quality of Service |
| MAC | Medium Access Control |
| PDR | Packet Delivery Ratio |
| AMAC | Adaptive Multi-channel Assignment and Coordination Scheme |
| CCBR | Control Channel Busy Ratio |
| PNP | Peer-to-Peer Negotiation Phase |
| VER-MAC | Efficient and Reliable MAC protocol for VANETs |
| WHO | World Health Organization |
| MIROS | Malaysian Institute of Road Safety Research |
| ITSs | Intelligent Transportation Systems |
| MANETs | Mobile Ad-hoc Networks |
| GPS | Global Positioning System |
| OBU | On-board Unit |
| RSU | Roadside Unit |
| V2V | Vehicle-to-Vehicle |
| V2I | Vehicle to Infrastructure |
| HV | Hybrid Vehicular |
| DSRC | Dedicated Short-Range Communication |
| WAVE | Wireless Access in Vehicular Environment |
| PHY | Physical layer |

| | |
|---|---|
| OFDM | Orthogonal Frequency Division Multiplex |
| EDCA | Enhanced Distributed Channel Access |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance |
| CWs | Contention Windows |
| AIFS | Arbitration Inter-Frame Spaces |
| FCC | Federal Communications Commission |
| CCHI | CCH Interval |
| SCHI | SCH Interval |
| RFS/ACK | Request For Service /Acknowledgement |
| NS-2.34 | Network Simulator-2.34 |
| OSM | OpenStreetMap |
| SUMO | Simulation of Urban Mobility |
| HS | Hotspots |
| WiMAX | Worldwide Interoperability for Microwave Access |
| GSM | Global System Mobile Communications |
| UMTS | Universal Mobile Telecommunications System |
| LTE-Advanced | Long-Term Evolution-Advanced |
| SV2V | Single-hop V2V |
| MV2V | Multi-hop V2V |
| SV2I | Sparse V2I |
| UV2I | Ubiquitous V2I |
| BSS | Basic Service Set |
| STAs | Stations |
| IBSS | Independent BSS |
| WBSS | WAVE Basic Service Set |
| WSMP | WAVE Short Message Protocol |

| | |
|---|---|
| EIVP | European ITS VANET Protocol |
| AP | Access Point |
| DS | Distribution System |
| ESS | Extended Service Set |
| ASTM | American Society for Testing and Materials |
| ACs | Access Categories |
| AC_BK | Background |
| AC_BE | Best Effort |
| AC_VI | Video |
| AC_VO | Voice |
| SI | Synchronization Interval |
| UTC | Coordinated Universal Time |
| IPv6 | Internet Protocol version 6 |
| DCF | Distributed Coordination Function |
| RTS/CTS | Request-To-Send/Clear-To-Send |
| TXOP | Transmission Opportunity |
| EDCAF | Enhanced Distributed Channel Access Function |
| SIFS | Short Inter-Frame Spacing |
| PIFS | PCF Inter-Frame Space |
| DIFS | DCF Inter-Frame Space |
| AIFSN | Inter-Frame Spacing Numbering |
| ACK | Acknowledgment |
| VCS | Virtual Carrier Sensing |
| NAV | Network Allocation Vector |
| TDMA | Time Division Multiple Access |
| CDMA | Code Division Multiple Access |

| | |
|---|---|
| FDMA | Frequency Division Multiple Access |
| RTTs | Round Trip Times |
| CBA | Collision-based Beacon Rate Adaptation scheme |
| ATB | Adaptive Traffic Beacon scheme |
| SNR | Signal-to-Noise Ratio |
| IPCS | Incremental Power Carrier Sensing |
| AOS | Adaptable Offset Slot |
| SR-CSMA | Safety Rang-CSMA |
| DTRA | Dynamic Transmission-Range Assignment |
| D-FPAV | Distributed Fair Power Adjustments for Vehicular environments |
| DID-MMAC | Dynamic Interval Division Multi-channel MAC |
| SAP | Service Announcement Phase |
| BP | Beacon Phase |
| PRP | Peer-To-Peer Reservation Phase |
| VCI | Variable CCH Interval scheme |
| MP-MAC | Multiple Priority based on p-persistent MAC |
| CAVI-MAC | Context Aware Variable Interval MAC |
| I-BSS | Intra Basic Service Set |
| APDM | Adaptive Multi-Priority Distributed Multi-Channel scheme |
| ORP | Optimal Ratio Packet |
| ON | Optimized Node |
| AMCMAC-D | Asynchronous Multi-Channel MAC with Distributed Time Division Multiple-Access Mechanism |
| CS-TDMA | Scalable CSMA and Self-organizing TDMA MAC scheme |
| WSD | WAVE-enhanced Safety message Delivery |
| OCA | Optimal Channel Access algorithm |

| | |
|---|---|
| MTA | Mobility and Topology Aware algorithm |
| W-HCF | WAVE-based Hybrid Coordination Function |
| TXOP REQ | TXOP Request |
| TXOP RSP | TXOP Response |
| TXOP ACK | TXOP Acknowledgement |
| UOTabu | Uni-Objective Tabu scheme |
| AMRC | Adaptive Message Rate Control scheme |
| DCCS | Dynamic Congestion Control Scheme |
| BER | Bit Error Rate |
| FERs | Frame Error Rate |
| QPSK | Quadrature Phase Shift Keying modulation |
| 1-D and 2-D | 1 and 2 Dimensional Markov Chain |
| np | Number of Packets |
| OCA | Optimal Channel Access |

## CHAPTER 1

## INTRODUCTION

The subject of Vehicular Ad hoc Networks (VANETs) has attracted tremendous interest among governmental sectors, industries, and academic institutions due to their significant applications in the sustainable safety environment. Although vehicular networks were initially developed to provide safety and traffic efficiency related applications, the role of infotainment and commercial services among vehicles has rapidly become critical where Internet access is required [1]. Thus, VANETs services have become more advanced to provide multiple applications, such as road safety, traffic efficiency, infotainment, and commercial service applications [2]. As a result, Quality of Service (QoS) provisioning is required in vehicular communications to ensure reliable and efficient dissemination of VANETs applications. This chapter first highlights the limitations and problems of the existing works in VANETs. The chapter then describes the main objectives of the thesis, followed by the scope and contributions of the research. Finally, this chapter outlines the thesis organization.

### 1.1 Background and Motivation

Recently, with increase in the population, the number of registered vehicles has dramatically increased over all the world, and this leads to a high rate of traffic accidents on the roads. In fact, traffic accidents are the ninth most common cause of death according to a report has been released by the World Health Organization (WHO) [3], [4]. In the United States, the average number of deaths owing to vehicle crashes was 36,000 annually from 1994 to 2012, according to the National Highway Traffic Safety Administration [5], [6]. Similarly, in Malaysia, an average of 23,252,409 vehicles were registered from 2010 to 2015. This huge number of registered vehicles along with the limited capacity of roads and highways have caused 461,481 road crashes, 6,826 road deaths, and 5,521 serious injuries annually from 2010 to 2015 according to a report by the Malaysian Institute of Road Safety Research (MIROS) [7]. Therefore, in order to prevent such accidents, an Intelligent Transportation Systems (ITSs) is needed to be installed to notify the drivers immediately of the obstacles in front of them. Researchers have found that road accidents can be significantly reduced if drivers receive warning information about the traffic hazards 0.5 seconds in advance [8], [9].

However, Vehicular Ad-hoc Networks (VANETs) are the key component of an ITS which integrates wireless networks into vehicles. VANETs are a sub-class of Mobile Ad-hoc Networks (MANETs) with several different characteristics that distinguish them from MANETs. VANETs differ in terms of large number of nodes, high mobility, rapid network topology change, no power constraints, and availability of Global Positioning System (GPS). A GPS system is used to collect information about vehicles, such as position, speed, and direction, etc. Thus, due to the unique features of VANETs, the medium access control (MAC) protocols designed for MANETs are not applicable to VANETs technology [6]. VANETs exploit an On-board Unit (OBU) and Roadside Unit (RSU) to achieve Vehicle-to-Vehicle (V2V), Vehicle to Infrastructure (V2I), and Hybrid Vehicular (HV) communications as in Figure 1.1 [7]. The communication in VANETs is either direct if the vehicles are within the transmission range of each other, or they cooperate in a multi-hop fashion so as to send packets from source to destination.

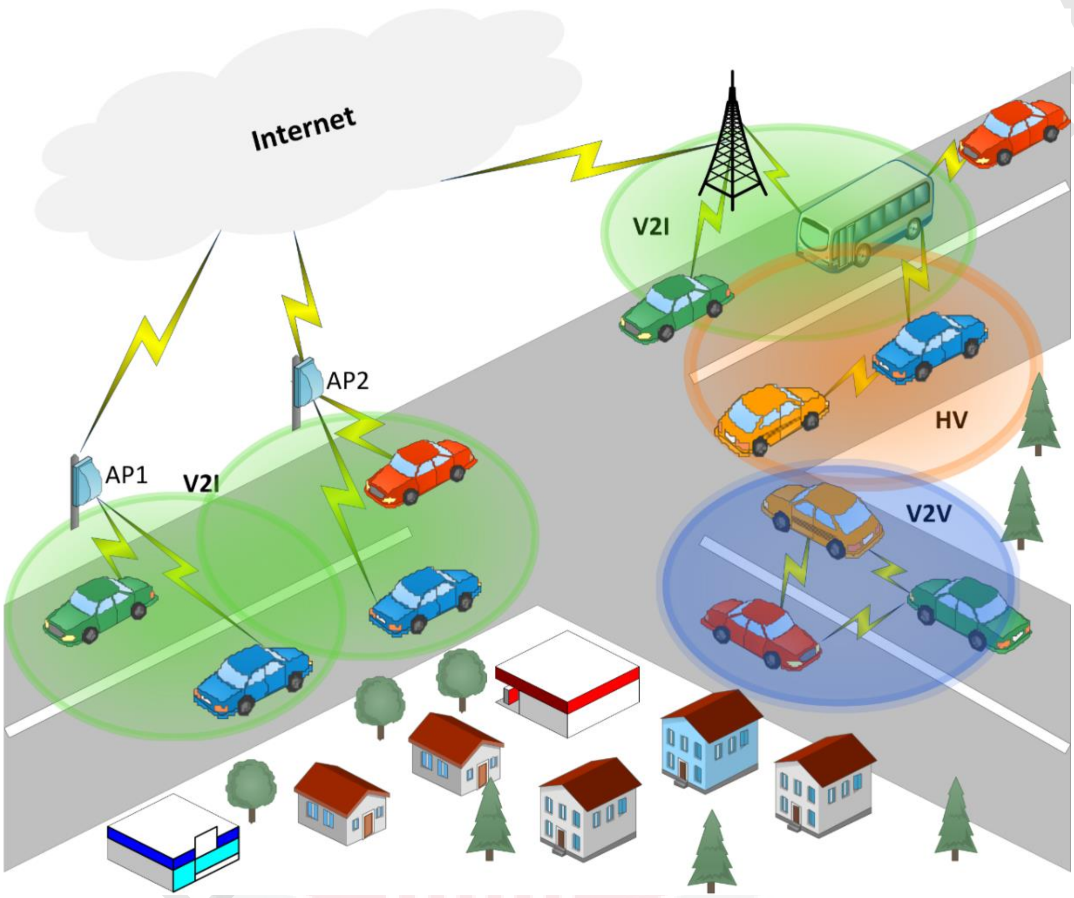


**Figure 1.1 : VANETs system architecture, Vehicle-to-Vehicle, Vehicle-to-Infrastructure and Hybrid Communications**

VANETs are promising in terms of reducing accident fatalities, improving road safety and traffic efficiency, and providing infotainment as well as commercial services among vehicles on the road. Thus, the applications of VANETs are divided based on prioritization into two categories, safety applications with higher priority and service applications with lower priority. The safety applications include; a) event-driven messages (emergency messages are usually related to safety of life such as electronic brake warning, post-crash notification and oncoming traffic warning); and b) periodic messages which give information on the current status of vehicles to control the traffic (position, speed, and direction, etc.). On the other hand, the service applications aim to improve driving comfort and the efficiency of transportation such as parking availability notification, parking payment, electronic toll collection, service announcements, digital maps, media downloading and internet services. Safety applications are typically delay-sensitive, while service applications are throughput-sensitive. Therefore, the safety applications require higher priority to ensure communication reliability and timely packet transmission.

Dedicated Short-Range Communication (DSRC) and Wireless Access in Vehicular Environment (WAVE) are the main standard protocols designed for VANETs by the IEEE community. DSRC is the wireless technology developed based on Wi-Fi to be used in very high dynamic networks in order to provide reliable communication and minimum latency of transmitted packets. The WAVE stack has been developed based on the IEEE 802.11p and IEEE 1609.x standards to operate under the DSRC band. IEEE 1609.x family includes IEEE 1609.0, 1609.1, 1609.2, 1609.3, 1609.4 [11], 1609.5, 1609.6, 1609.11, and 1609.12**.** This dissertation focuses on the IEEE 802.11p and IEEE 1609.4 standards. The Physical layer (PHY) of IEEE 802.11p was adopted from IEEE 802.11a PHY based on Orthogonal Frequency Division Multiplex (OFDM) technology with some minor changes to fit well with high-speed vehicular environment. The IEEE 1609.4 standard has been designed to support multi-channel operation in the DSRC band. Particularly, it enhances the structures of the IEEE 802.11p MAC sub-layer and coordinates the multi-channel operations. The MAC sub-layer of IEEE 802.11p uses Enhanced Distributed Channel Access (EDCA) which is derived from IEEE 802.11e to improve the Quality of Service (QoS) [12], [13]. EDCA is a contention-based MAC scheme as in IEEE 802.11 MAC relying on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to access the channel. The prioritized EDCA scheme is the core of the MAC layer. Thus, the prioritization of EDCA scheme is achieved by changing the Contention Windows (CWs) and the Arbitration Inter-Frame Spaces (AIFS) sizes, which increase the probability of successful medium access for real-time messages. Specifically, higher priority applications (safety applications) are given smaller value of CW size and shorter value of AIFSs to get a better chance of being transmitted than applications with a lower priority (service applications).

Moreover, in order to provide different types of applications in different channels frequencies in VANETs, the Federal Communications Commission (FCC) has allocated a frequency band of *5.9 GHz* in a total bandwidth of *75 MHz* under the DSRC standard. This bandwidth supports seven channels, each of which is *10 MHz* wide and the guard band is *5 MHz* wide [13]. These channels are functionally divided into one control channel (CCH_178), and up to six are service channels (SCHs). The CCH is exclusively used to broadcast safety-critical applications and regular traffics, while the six other channels, SCHs, are dedicated to transfer service data applications. Regular traffic contains periodic short status heartbeat messages (beacons), and WAVE Service Announcements (WSAs). WSAs contain information related to the services offered on the SCH and the network parameters necessary to join the provider (provider Service ID, selected SCH, channel access parameters, etc.). The repeating synchronization intervals (SI) for the channels to transmit the packets are *100 ms*, and each SI is divided into CCH Interval (CCHI) of *50 ms* and SCH Interval (SCHI) of *50 ms* [11]. According to the standard IEEE 1609.4 specifications of multi-channels operation, during CCHI, the channel activity on all service channels is suspended and vice versa [14]. It is mandatory for all vehicles to stay on the CCH to monitor the channel for safety and WSAs applications during the CCHI, while during SCHI, the vehicles can optionally switch to SCHs to transmit service data applications according to the coordination scheme rules. This method enables the transmission of safety and service applications in different channels, without missing significant safety applications on the CCH. Typically, packets collision may occur if more than one vehicle starts transmitting a packet simultaneously within the same time slot. Transmission error, on the other hand, may manifest due to the complex condition of a wireless channel in VANETs such as path loss, thermal noise, channel fading, or interference from other radio resources. Moreover, a congestion channel occurs when many vehicles compete to acquire the channel using the same radio frequency.

However, in VANETs, CCH is dedicated to broadcast multiple types of applications sharing a common frequency. Hence, the channel congestion may occur during heavy traffic conditions leading to a deterioration in the performance of VANETs with high collisions rates and low packet delivery ratio (PDR) of transmitted packets. In order to improve the performance of VANETs with reducing collisions and increasing PDR of transmitted packets on CCH, QoS support is required. Indeed, the performance of VANETs and QoS are directly proportional, where high QoS results in high level of performance of VANETs. The QoS provisioning always guarantees reliable and efficient data dissemination in vehicular communications. One of the effective approaches to support the QoS in VANETs is the channel congestion control, which will be studied in this thesis. In fact, the channel congestion control has been extensively studied for cellular networks and MANETs. Due to the unique features of VANETs, the channel congestion control mechanisms proposed for MANETs are not direct solutions to channel congestion in VANETs. Thus, channel congestion control for IEEE 802.11p/1609.4 based MAC VANETs is still a relatively open research area. It can be performed by using one of the following approaches; controlling packet transmission rate, modifying CSMA/CA protocol, controlling transmission power, prioritizing and scheduling messages, and hybrid approach. The main idea of controlling packet transmission rate is to adjust the transmission rate or packet generation rate according to the channel condition on the network to address the channel congestion problem. In modifying CSMA/CA protocol, the channel congestion control can be achieved by modifying the CW size and AIFS values dynamically based on the channel conditions. In controlling transmission power, the transmission power or range is dynamically adjusted according to the condition of channel load to control the channel congestion problem. The prioritizing and scheduling messages approach determines a priority for each message and schedules them in control and service channels queues, such that the emergency and safety messages are given higher priorities while service messages are given lower priorities in accessing the channel. Finally, the hybrid approach is performed by combining all or some of the aforementioned four categories of channel congestion control approaches to address the channel congestion in VANETs, which will be studied in this thesis.

## 1.2 Problem Statement

Vehicular ad-hoc networks provide different types of applications to all classes of vehicles, either private or public transportation. Although vehicular networks were initially developed under ITS to improve road safety and traffic efficiency, the role of infotainment and commercial services among vehicles has rapidly become critical where Internet access is required [1]. Subsequently, the applications of VANETs are classified into safety, traffic efficiency, infotainment, and commercial service applications [2]. In 2006, the IEEE 1609.4 standard for WAVE has been designed to support multi-channel operations in VANETs in order to enable the transmission of safety and service applications in different channels [11]. These channels are functionally divided into one common control channel (CCH_178), and up to six service channels (SCHs). The CCH is exclusively used to broadcast safety-critical applications and regular traffic such as beacons and WAVE Service Announcements (WSAs), while the six other channels, SCHs, are dedicated to transfer service data applications. The repeating synchronization intervals (SI) for the channels to transmit the packets are *100 ms*, and each SI is divided into CCH Interval (CCHI) of *50 ms* and SCH Interval (SCHI) of *50 ms* [11]. According to the standard IEEE 1609.4 specifications of multi-channels operation, the channel activity on all SCHs is suspended during CCHI and vice versa [14]. It is mandatory for all vehicles to stay on the CCH to monitor the channel for safety, beacons, and WSA applications during the CCHI, while during SCHI the vehicles can optionally switch to SCHs to transmit service data applications.

However, since the traffic and topology are unstable and frequently change in vehicular networks, the fixed division of SI between the CCH and SCHs does not fit with the real vehicular network environment [15]-[18]. This is because it cannot provide proper bandwidth to achieve time-bounded delay and high system throughput for both safety and service applications respectively. For instance, if the remaining time for the CCHI is shorter than the transmission time of a safety application, a vehicle will be unable to disseminate a safety application, which will be dropped when its lifetime has expired. On the other hand, if the traffic condition is light (sparse), the transmission of safety applications on the CCH will be occasional. Consequently, the CCH resources and interval will be wasted, whereas bulk service data cannot obtain enough time to be transmitted on SCHs during the SCHI. In addition, increasing CCHI will absolutely increase the transmission of safety and control applications, and decrease the time share of SCHs. For these reasons, several approaches have been proposed for resolving this issue. Some of these proposed solutions include variable CCHI multi-channel MAC scheme, where the length ratio between the CCH and SCHs was dynamically adjusted based on the traffic conditions [15]-[19]. Moreover, four modalities of channel access in case of a single-radio device have lately been recommended by the IEEE 1609.4 standard in 2010 and 2016 [20], which are continuous CCH access, alternating CCH and SCH access, immediate SCH access, and extended SCH access scheme. However, the criteria and procedures for selecting the channel access scheme type and measuring the level of congestion on the channel are not specified in the IEEE 1609.4 standard. The policy of selecting a SCH type and setting up non-overlapping time intervals over the same SCH frequency by the providers are also not clearly defined in the IEEE 1609.4 standard.

In summary, the following problems have been identified and will be addressed in the thesis:

1. The existing analytical models of IEEE 802.11p/1609.4-based MAC in VANETs assume that the wireless channel is error-free (ideal) [22]-[24]. Such assumption is inaccurate, especially when dealing with a decentralized wireless network as in VANETs. They also consider the packet arrival rate while ignoring the presence of the buffer memory [21]. This results in a significant delay in packet transmission and underutilization of the channel.
2. In VANETs, CCH is dedicated to broadcast multiple types of applications sharing a common frequency [25], [87]. According to the legacy approach and other existing works, the SCH communications resource reservation mechanism (peer-to-peer negotiation phase (PNP)) between service providers and users is implemented over the CCH during the fixed CCHI [25], [87]. Consequently, in heavy traffic, the CCH will be congested, and the safety packets may suffer from severe collisions with other control packets such as WSAs and Request For Service /Acknowledgement (RFS/ACK). This will lead to a deterioration in the performance of VANETs with higher rates of collisions and delay, as well as lower packet delivery ratio (PDR) of transmitted safety packets over CCH.
3. If the traffic conditions are heavy, at the beginning of each CCHI, huge backlogged vehicles contend to transmit packets through common wireless channel using same radio frequency under default CWs sizes values [26]. Accordingly, the probability of packets collision and the average delay will increase with increasing the number of competing vehicles and the number of packets per vehicle. Also, the transmission of safety applications in VANETs follows broadcast mode in which the failed broadcast packet will never be detected due to the lack of acknowledgement exchange among vehicles [27]-[29] and [87]. As a result, the CW size value for safety applications remains constant, and hence the collisions of safety packets are increased in heavy network conditions. Based on the foregoing, the QoS in VANETs technology is still low.

## 1.3 Aim and Objectives

The main goal of this research work is to propose congestion control mechanisms for IEEE 802.11p/1609.4 in VANETs in order to guarantee high QoS in vehicular network environment. To accomplish this, the study aims to achieve the following specific objectives:

1. To design analytical models of IEEE 802.11p/1609.4 scheme in VANETs for safety and service application based on Markov chain in the present of error-prone channel.
2. To develop an adaptive PNP execution mechanism between service providers and users for SCHs resource reservations.
3. To propose a collision-aware packet transmission mechanism at the beginning of each CCHI in order to improve the time diversity among vehicles.

## 1.4 Thesis Scope

This research focuses on providing channel congestion control mechanisms for IEEE 802.11p/1609.4 in VANETs. The proposed mechanisms support multi-channel operations (CCH and SCHs) in VANETs under DSRC band. However, this research considers both broadcast and unicast transmission schemes. The issues of packet arrival rate, buffered packet transmission rate, error-prone channels, multi-channel hidden terminal, and overlapping intervals over the same SCH radio frequency are studied in this work. Initially, the analytical models of IEEE 802.11p/1609.4 scheme in VANETs for safety and service application based on Markov chain are designed. These analytical models take into account the error-prone channels, and the packet arrival rate along with the first order buffer memory in order to guarantee an accurate system throughput and utilize the channel efficiently. Then the Control Channel Busy Ratio (CCBR) is calculated by RSU in this research. Based on the CCBR value, three mechanisms are executed in MAC layer. These mechanisms include channel access scheme type selection, adaptive PNP execution, and collision-aware packet transmission as shown in Figure 1.2. The PNP mechanism between service providers and users for SCHs resource reservations is adaptively executed either over CCH or SCHs according to the CCH conditions (CCBR value). The collision-aware packet transmission mechanism at the beginning of each CCHI can improve the time diversity among vehicles. Therefore, the probability of collision rate and delay of safety applications will be reduced. The impact of the vehicle speed and the multi-hop broadcast are not studied in this research. Furthermore, the developed mechanisms are modelled and validated using simulation by Network Simulator-2.34 (NS-2.34). The utilized radio communication technology is the IEEE 802.11p where its MAC sub-layer characteristics are implemented. No testbed evaluations are conducted.

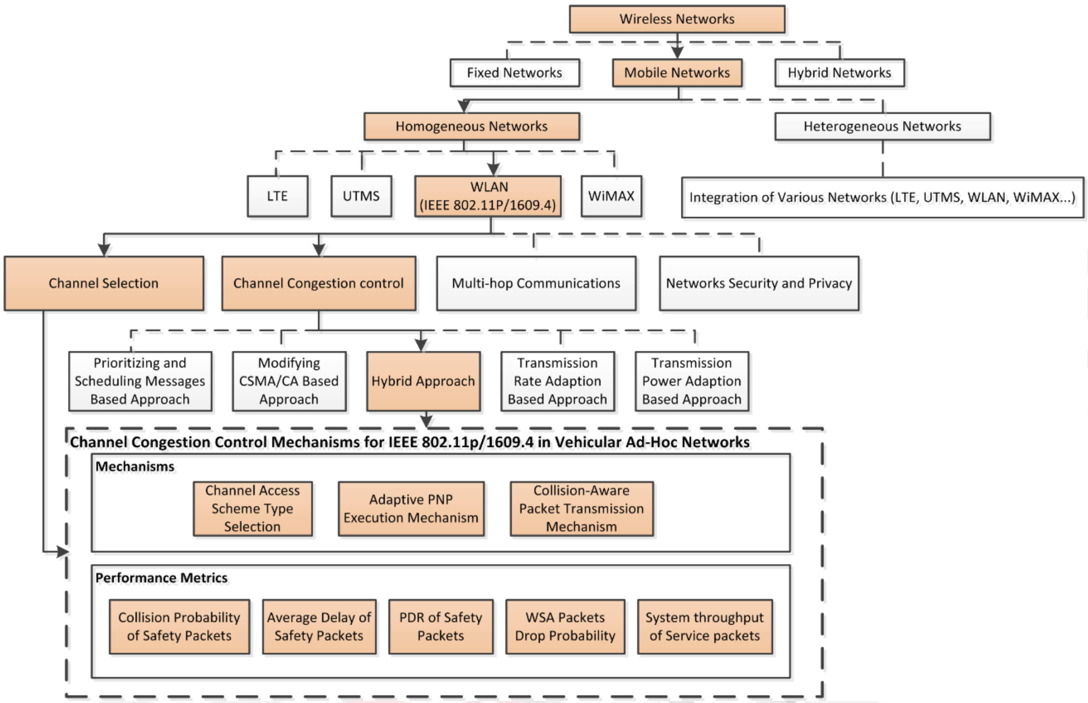


**Figure 1.2 : Study module**

## 1.5 Thesis Contributions

The key contributions of this research to the literature can be summarized as follows:

***A. Analytical formulation to predict the performance of IEEE 802.11p/1609.4 in VANETs.***

The analytical 1-D and 2-D Markov chain models represent the transmission probability for safety and service applications under non-saturated conditions, respectively. The proposed analytical models are an extension of the existing models presented in [24] to analyze the mathematical model of the back-off procedure for IEEE 802.11p/1609.4-based MAC layer. The proposed analytical models are more accurate compared to the existing ones [24] in terms of adopting many variables on models. The proposed analytical models adopt the error-prone channels to avoid overestimating system throughput. The back-off timer freezing, the packet arrival rate along with the first order buffer memory and the M/M/1 queue are also taken into consideration to provide an accurate estimation of the channel access, efficient utilization of the channel, and analysis of the time performance. Moreover, back-off stages along with short retry limit for service applications in the models are also taken into account to accommodate the IEEE 802.11p specifications and to guarantee that no packet is served indefinitely. Finally, the probabilities of successful transmission, transmission error, collisions, and WSA packets drop have been derived to compute PDR, and average delay of safety applications, as well as the system throughput of service applications. Analysis of these metrics is useful for assessing the performance of IEEE 802.11p/1609.4 in VANETs in the thesis.

***B. A new congestion control mechanism that reduces the number of transmitted packets over CCH if the CCH is congested.***

This mechanism first proposes an Adaptive Multi-Channel Assignment and Coordination (AMAC) scheme for IEEE 802.11p/1609.4 in VANETs. In AMAC scheme, the RSU estimates the CCBR based on the number of received packets from vehicles located around its coverage range. Consequently, the PNP mechanism between service providers and users for SCHs resources reservations is adaptively executed according to the CCH conditions (CCBR value); (i) over the CCH if the traffic condition is light, which helps to exploit the CCH resources and interval efficiently; (ii) over the SCHs if the traffic condition is heavy in order not to adversely affect the delivery of safety applications over the CCH. As a result, employing this mechanism will preserve the transmission of safety applications over CCH from high collisions and delay, and thus the QoS will be improved in VANETs. In addition, the RFS/ACK handshaking (PNP) interaction between providers and users assists in addressing the multi-channel hidden terminal problem, ensuring different SCH selection, and reserving a non-overlapping time interval over the same SCH radio frequency.

***C. A new congestion control mechanism that improves the time diversity among vehicles within the CCH known as collision-aware packet transmission mechanism.***

The mechanism is based on the number of active vehicles located within the same transmission range. This mechanism is achieved by modifying CSMA/CA protocol. Specifically, the CWs size values for safety and service applications are dynamically adjusted based on the number of competing vehicles. The RSU first calculates the number of active vehicles within its radio coverage range. Accordingly, it broadcasts a special packet at the beginning of each CCHI that includes the best values of CW sizes to be adopted by the vehicles within its radio coverage area. As a result, the time diversity among vehicles will be improved, and thus, the probability of collision rate and delay of safety applications will be reduced. Finally, employing the collision-aware packet transmission mechanism to the system will enhance the QoS in VANETs by increasing the PDR of transmitted packets.

***D. New NS2 modules implement the proposed congestion control mechanisms.***

The modules include modifications on the sources of C++ files of the MAC802.11.ext as well as in some of the OTCL files, such as the *mobile_node* and *mobile_default* files. The modules are implemented for simulating the functionalities of the proposed mechanisms, and thereby for investigating the performance of the proposed mechanisms through comparison with other mechanisms. In the simulation, Shah Alam highway is assumed to simulate the scenario. The map of Shah Alam highway was taken from OpenStreetMap (OSM) [30], and used by Simulation of Urban MObility (SUMO) [31] to generate vehicle movement.

## 1.6 Thesis Organization

This thesis shows how to design and develop channel congestion control mechanisms for IEEE 802.11p/1609.4 in VANETs with consideration of error-prone channels. The organization of this thesis is as follows. Chapter 1 presents an introduction of VANETs, stating the research problem and then objectives, and finally the contributions introduced by the thesis are summarized.

Chapter 2 first presents an overview of VANETs, architectures, communication patterns and applications. It then describes the functional entities and standardization in VANETs. Next, it provides a brief review of communications-based MAC protocols in VANETS including contention-based MAC protocol, contention-free MAC protocol, and Hybrid MAC protocol. Survey of previous analytical models for IEEE 802.11p/1609.4 scheme in VANETs communication is critically reviewed. The congestion control approaches in VANETs are also discussed, including proactive, reactive, and hybrid approaches as well as congestion detection methods. Finally, in this chapter, the previous approaches related to channel congestion control based on QoS parameters are comprehensively reviewed. These approaches are classified into five categories including transmission rate adaption-based approach, modifying CSMA/CA based approach, transmission power adaption-based approach, prioritizing and scheduling messages-based approach, and hybrid approach.

Chapter 3 introduces the general methodology followed in this research. Next, the analytical model of IEEE 802.11p/1609.4-based MAC in the presence of error-prone channels under non-saturated conditions are well presented. In addition, the development of the congestion control channel mechanisms under AMAC scheme in VANETs are discussed. This chapter also introduces the simulation model and metrics for evaluating the performance of the proposed mechanisms. Finally, the simulation framework is also explained illustrating the simulation tools, simulation topologies and mobility scenario.

Chapter 4 evaluates the performance of IEEE 802.11p/1609.4 scheme. The results of the analytical model of 802.11p/1609.4 scheme are benchmarked with existing model in [24]. The chapter also evaluates the performance of the proposed AMAC scheme. The results of the proposed AMAC scheme are benchmarked with VER-MAC scheme [87]. Finally, the chapter discusses the results and summarizes the finding. Chapter 5 summarizes the conclusions drawn from the work presented in this research, and discusses directions for future work.

## REFERENCES


[1] S. Céspedes, X. Shen, and C. Lazo, "IP mobility management for vehicular communication networks: challenges and solutions," *IEEE Communications Magazine,* vol. 49, 2011.

[2] H. Hartenstein and K. P. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Communications magazine,* vol. 46, p. 164, 2008.

[3] A. Abdelfatah, "Traffic Fatality Causes and Trends in Malaysia," *American University of Sharjah, Massachusetts Institute of Technology,* 2016.

[4] W. H. O. Violence, I. Prevention, and W. H. Organization, *Global status report on road safety 2013: supporting a decade of action*: World Health Organization,2013, http://www.who.int/violence_injury_prevention/road_safety_status/2013/en/ [13 August 2018].

[5] H. P. Luong, "Vehicle-to-vehicle broadcast for highway safety applications," 2017.

[6] NHTSA (2013). The National Highway Traffic Safety Administration. http://www.nhtsa.gov/NCSA.

[7] MIROS (1997 - 2016). The Malaysian Institute of Road Safety Research. https://www.miros.gov.my/1/page.php?id=17 [13 August 2018].

[8] K. A. Hafeez, "Design and analysis of an efficient and reliable MAC protocol for VANETS," Toronto: Ryerson University, 2012: 8-15, 2012.

[9] S. A. Gillani, P. A. Shah, A. Qayyum, and H. B. Hasbullah, "MAC layer challenges and proposed protocols for vehicular ad-hoc networks," in *Vehicular Ad-hoc Networks for Smart Cities,* ed: Springer, 2015, pp. 3-13.

[10] M. L. Sichitiu and M. Kihl, "Inter-vehicle communication systems: a survey," *IEEE Communications Surveys & Tutorials,* vol. 10, 2008.

[11] IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi Channel Operation, IEEE Std 1609.4-2006, November 2006.

[12] I. S. Association, "802.11 p-2010—ieee standard for information technology—local and metropolitan area networks—specific requirements—part 11: Wireless lan medium access control (MAC) and physical layer (PHY) specifications amendment 6: Wireless access in vehicular environments,"

[13] A. A. Almohammedi, N. K. Noordin, and S. Saeed, "Evaluating the Impact of Transmission Range on the Performance of VANET," *International Journal of Electrical and Computer Engineering (IJECE),* vol. 6, pp. 800-809, 2016.

[14] C. Campolo, A. Molinaro, A. Vinel, and Y. Zhang, "Modeling prioritized broadcasting in multichannel vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 61, pp. 687-701, 2012.

[15] Q. Wang, S. Leng, H. Fu, and Y. Zhang, "An IEEE 802.11 p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, pp. 449-458, 2012.

[16] C. Shao, S. Leng, Y. Zhang, and H. Fu, "A multi-priority supported medium access control in Vehicular Ad Hoc Networks," *Computer Communications*, vol. 39, pp. 11-21, 2014.

[17] S. Babu, M. Patra, and C. S. R. Murthy, "A novel context-aware variable interval MAC protocol to enhance event-driven message delivery in IEEE 802.11 p/WAVE vehicular networks," *Vehicular Communications*, vol. 2, pp. 172-183, 2015.

[18] K. A. Hafeez, A. Anpalagan, and L. Zhao, "Optimizing the control channel interval of the dsrc for vehicular safety applications," *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 3377-3388, 2016.

[19] C. Song, G. Tan, C. Yu, N. Ding, and F. Zhang, "APDM: An adaptive multi-priority distributed multichannel MAC protocol for vehicular ad hoc networks in unsaturated conditions," *Computer Communications*, vol. 104, pp. 119-133, 2017.

[20] IEEE Standard for Wireless Access in Vehicular Environments (WAVE)-Multi-channel Operation, IEEE Std 1609.4-2016, (Revision of IEEE Std 1609.4-2010), 2016.

[21] N. Gupta and C. S. Rai, "Performance Evaluation of IEEE 802.11 DCF in Single Hop Ad Hoc Networks," *Wireless personal communications*, vol. 79, pp. 2171-2193, 2014.

[22] Y. Yao, L. Rao, and X. Liu, "Performance and reliability analysis of IEEE 802.11 p safety communication in a highway environment," *IEEE transactions on vehicular technology*, vol. 62, pp. 4198-4212, 2013.

[23] P. Rathee, R. Singh, and S. Kumar, "Performance Analysis of IEEE 802.11 p in the Presence of Hidden Terminals," *Wireless Personal Communications*, vol. 89, pp. 61-78, 2016.

[24] D. N. M. Dang, Q. T. Ngo, H. N. Dang, and P. L. Vo, "Analytical Study of the IEEE 1609.4 MAC in Vehicular Ad Hoc Networks," in *International Conference on Advanced Engineering Theory and Applications*, 2017, pp. 145-154.

[25] M. Amadeo, C. Campolo, and A. Molinaro, "Enhancing IEEE 802.11 p/WAVE to provide infotainment applications in VANETs," *Ad Hoc Networks*, vol. 10, pp. 253-269, 2012.

[26] C. Campolo, A. Molinaro, and A. Vinel, "Understanding the performance of short-lived control broadcast packets in 802.11 p/WAVE vehicular networks," in *Vehicular Networking Conference (VNC), 2011 IEEE*, 2011, pp. 102-108.

[27] A. J. Ghandour, M. Di Felice, H. Artail, and L. Bononi, "Dissemination of safety messages in IEEE 802.11 p/WAVE vehicular network: Analytical study and protocol enhancements," *Pervasive and mobile computing*, vol. 11, pp. 3-18, 2014.

[28] Q. Yang, S. Xing, W. Xia, and L. Shen, "Modelling and performance analysis of dynamic contention window scheme for periodic broadcast in vehicular ad hoc networks," *IET Communications*, vol. 9, pp. 1347-1354, 2015.

[29] S. Wang, B. Yang, F. Gu, and X. Shi, "A novel reliable broadcast protocol for VANET's safety applications," in *Electronics Information and Emergency Communication (ICEIEC), 2016 6th International Conference on*, 2016, pp. 282-286.

[30] OpenStreetMap: The FreeWikiWorld Map, 2008. http://www.openstreetmap.org/ [13 August 2018]

[31] SUMO. 2001. Simulation of Urban Mobility. http://sumo.sourceforge.net/ [13 August 2018]

[32] A. Marshall, "V2V: GM technology can prevent accidents," *GM Europe*, 2006.

[33] C. C. C. Consortium, "Car 2 car communication consortium manifesto," *Braunschweig, November*, 2007.

[34] H. Moustafa and Y. Zhang, *Vehicular networks: techniques, standards, and applications*: Auerbach publications, 2009.

[35] M. Kaur, "Vehicular ad hoc networks," *Journal of Global Research in Computer Science*, vol. 3, pp. 61-64, 2012.

[36] A. Festag, G. Noecker, M. Strassberger, A. Lübke, B. Bochow, M. Torrent-Moreno, *et al.*, "'NoW–Network on Wheels': Project objectives, technology and achievements," 2008.

[37] L. Nassar, A. Jundi, K. Golestan, F. Sattar, F. Karray, M. Kamel, *et al.*, "Vehicular ad-hoc Networks (VANETs): capabilities, challenges in context-aware processing and communication gateway," in *Autonomous and Intelligent Systems*, ed: Springer, 2012, pp. 42-49.

[38] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, *et al.*, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE communications surveys & tutorials*, vol. 13, pp. 584-616, 2011.

[39] S. Zeadally, R. Hunt, Y.-S. Chen, A. Irwin, and A. Hassan, "Vehicular ad hoc networks (VANETS): status, results, and challenges," *Telecommunication Systems*, vol. 50, pp. 217-241, 2012.

[40] T. ETSI, "Intelligent transport systems (ITS); vehicular communications; basic set of applications; definitions," Tech. Rep. ETSI TR 102 6382009.

[41] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in DSRC," in *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks*, 2004, pp. 19-28.

[42] V. Nguyen, T. Anh Khoa, T. Zin Oo, N. H Tran, C. Seon Hong, and E.-N. Huh, "Time Slot Utilization for Efficient Multi-Channel MAC Protocol in VANETs," *Sensors*, vol. 18, p. 3028, 2018.

[43] N. Bouchemal, "Quality of Service Provisioning and Performance Analysis in Vehicular Network," Versailles-St Quentin en Yvelines, 2015.

[44] M. van Eenennaam, A. van de Venis, and G. Karagiannis, "Impact of IEEE 1609.4 channel switching on the IEEE 802.11 p beaconing performance," in *Wireless Days (WD), 2012 IFIP*, 2012, pp. 1-8.

[45] Z. Y. Rawashdeh and S. M. Mahmud, "Communications in vehicular networks," *Mobile Ad-Hoc Networks: Applications, Cap*, vol. 2, pp. 20-40, 2011.

[46] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, and R. Herrtwich, "Design of 5.9 GHz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, 2006.

[47] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proceedings of the IEEE*, vol. 99, pp. 1162-1182, 2011.

[48] M. Hadded, P. Muhlethaler, A. Laouiti, R. Zagrouba, and L. A. Saidane, "TDMA-based MAC protocols for vehicular ad hoc networks: a survey, qualitative analysis, and open research issues," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 2461-2492, 2015.

[49] F. Kargl, P. Papadimitratos, L. Buttyan, M. Müter, E. Schoch, B. Wiedersheim, *et al.*, "Secure vehicular communication systems: implementation, performance, and research challenges," *IEEE Communications magazine*, vol. 46, 2008.

[50] M. Gerlach and F. Guttler, "Privacy in VANETs using changing pseudonyms-ideal and real," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, 2007, pp. 2521-2525.

[51] IEEE Draft Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) -Resource Manager, IEEE Std 1609.1-206, October 2006.

[52] IEEE Standard for Wireless Access in Vehicular Environments Security Services for Applications and Management Messages, IEEE Std 1609.2-2013 (Revision of IEEE Std 1609.2-2006), April 2013.

[53] IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Networking Services, IEEE Std 1609.3-2010 (Revision of IEEE Std 1609.3-2007), December 2010.

[54] C. Campolo and A. Molinaro, "Multichannel communications in vehicular ad hoc networks: a survey," *IEEE Communications Magazine,* vol. 51, pp. 158-169, 2013.

[55] T. B. Reddy, J. P. John, and C. S. R. Murthy, "Providing MAC QoS for multimedia traffic in 802.11 e based multi-hop ad hoc wireless networks," *Computer Networks,* vol. 51, pp. 153-176, 2007.

[56] R. Rozovsky and P. Kumar, "SEEDEX: A MAC protocol for ad hoc networks," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, 2001, pp. 67-75.

[57] S. Bhandare, T. B. Brahim, S. Biaz, and P. Agrawal, "Performance evaluation of collision avoidance schemes in ad hoc networks," *Security and Communication Networks,* vol. 9, pp. 910-937, 2016.

[58] A. Jayasuriya, S. Perreau, A. Dadej, and S. Gordon, "Hidden vs exposed terminal problem in ad hoc networks," ATNAC 2004, 2004.

[59] S. Chakraborty, S. Nandi, and S. Chattopadhyay, "Alleviating hidden and exposed nodes in high-throughput wireless mesh networks," *IEEE Transactions on Wireless communications,* vol. 15, pp. 928-937, 2016.

[60] L. Wang, K. Wu, and M. Hamdi, "Combating hidden and exposed terminal problems in wireless networks," *IEEE Transactions on Wireless Communications,* vol. 11, pp. 4204-4213, 2012.

[61] Y. Xiao and Y. Pan, "Differentiation, QoS guarantee, and optimization for real-time traffic over one-hop ad hoc networks," *IEEE Transactions on Parallel & Distributed Systems,* pp. 538-549, 2005.

[62] C. de Morais Cordeiro and D. P. Agrawal, *Ad hoc and sensor networks: theory and applications*: World Scientific, 2011.

[63] B. Ducourthial, Y. Khaled, and S. Mottelet, "Fairness issues in a chain of IEEE 802.11 stations," *arXiv preprint arXiv:1102.3607*, 2011.

[64] S. Mangold and T. R. Gross, "A dual-radio contention-based protocol for paired spectrum access and TV white space," in *Wireless On-demand Network Systems and Services (WONS), 2012 9th Annual Conference on*, 2012, pp. 107-112.

[65] X. Fafoutis, C. Orfanidis, and N. Dragoni, "Altruistic backoff: collision avoidance for receiver-initiated mac protocols for wireless sensor networks," *International Journal of Distributed Sensor Networks*, vol. 10, p. 576401, 2014.

[66] K. Sjöberg, *Medium access control for vehicular ad hoc networks*: Chalmers University of Technology, 2013.

[67] C. Busch, M. Magdon-Ismail, F. Sivrikaya, and B. Yener, "Contention-free MAC protocols for wireless sensor networks," in *International Symposium on Distributed Computing*, 2004, pp. 245-259.

[68] A. Muqattash and M. Krunz, "CDMA-based MAC protocol for wireless ad hoc networks," in *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, 2003, pp. 153-164.

[69] A. Aragon-Zavala, *Antennas and propagation for wireless communication systems*: John Wiley & Sons, 2008.

[70] P. Revathi, R. Balasubramanian, R. K. Jain, S. S. Thakur, R. S. Kasana, S. Jain, *et al.*, "Estimated Bandwidth Distribution with Admission Control for Enhanced QoS Multicast Routing in MANETs," *Int. J. Advanced Networking and Applications*, vol. 1, pp. 69-75, 2009.

[71] M. X. Cheng and D. Li, *Advances in wireless ad hoc and sensor networks*: Springer Science & Business Media, 2008.

[72] C. Zhu and M. S. Corson, "QoS routing for mobile ad hoc networks," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 2002, pp. 958-967.

[73] Y. Y. Nasrallah, I. Al-Anbagi, and H. T. Mouftah, "A realistic analytical model of IEEE 802.11 p for Wireless Access in Vehicular Networks," in *Connected Vehicles and Expo (ICCVE), 2014 International Conference on*, 2014, pp. 1029-1034.

[74] D. N. M. Dang, H. N. Dang, and C. S. Hong, "Performance Analysis of the IEEE 802.11 p under Finite Traffic Conditions," in *AETA 2013: Recent Advances in Electrical Engineering and Related Sciences*, ed: Springer, 2014, pp. 191-199.

[75] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, "Analytical study of the IEEE 802.11 p MAC sublayer in vehicular networks," *IEEE Transactions on Intelligent Transportation Systems,* vol. 13, pp. 873-886, 2012.

[76] R. Woo, J.-H. Song, and D. S. Han, "Performance analysis for priority-based broadcast in vehicular networks," *International Journal of Distributed Sensor Networks,* vol. 9, p. 734637, 2013.

[77] D.-J. Deng, H.-C. Chen, H.-C. Chao, and Y.-M. Huang, "A collision alleviation scheme for IEEE 802.11 p VANETs," *Wireless Personal Communications,* vol. 56, pp. 371-383, 2011.

[78] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, and J. Gozalvez, "Congestion and awareness control in cooperative vehicular systems," *Proceedings of the IEEE,* vol. 99, pp. 1260-1279, 2011.

[79] Y. Zang, L. Stibor, X. Cheng, H.-J. Reumerman, A. Paruzel, and A. Barroso, "Congestion control in wireless networks for vehicular safety applications," in *Proceedings of the 8th European Wireless Conference*, 2007, p. 1.

[80] M. R. Jabbarpour, R. M. Noor, R. H. Khokhar, and C.-H. Ke, "Cross-layer congestion control model for urban vehicular environments," *Journal of Network and Computer Applications,* vol. 44, pp. 1-16, 2014.

[81] M. Y. Darus and K. A. Bakar, "Review of Congestion Control Algorithm for Event-Driven Safety Messages in Vehicular Networks," *International Journal of Computer Science Issues (IJCSI),* vol. 8, p. 49, 2011.

[82] M. S. Bouassida and M. Shawky, "On the congestion control within VANET," in *Wireless Days, 2008. WD'08. 1st IFIP*, 2008, pp. 1-5.

[83] J. He, H.-H. Chen, T. M. Chen, and W. Cheng, "Adaptive congestion control for DSRC vehicle networks," *IEEE communications letters,* vol. 14, pp. 127-129, 2010.

[84] X. Shen, X. Cheng, R. Zhang, B. Jiao, and Y. Yang, "Distributed congestion control approaches for the IEEE 802.11 p vehicular networks," *IEEE intelligent transportation systems magazine,* vol. 5, pp. 50-61, 2013.

[85] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: fair transmit power control for safety-critical information," *IEEE Transactions on Vehicular Technology,* vol. 58, pp. 3684-3703, 2009.

[86] M. Torrent-Moreno, "Inter-vehicle communications: assessing information dissemination under safety constraints," in *Wireless on Demand Network Systems and Services, 2007. WONS'07. Fourth Annual Conference on*, 2007, pp. 59-64.

[87] D. N. M. Dang, C. S. Hong, S. Lee, and E.-N. Huh, "An efficient and reliable MAC in VANETs," *IEEE Communications Letters,* vol. 18, pp. 616-619, 2014.

[88] N. Chaabouni, A. Hafid, and P. K. Sahu, "A collision-based beacon rate adaptation scheme (CBA) for VANETs," in *Advanced Networks and Telecommuncations Systems (ANTS), 2013 IEEE International Conference on*, 2013, pp. 1-6.

[89] F. Ye, R. Yim, S. Roy, and J. Zhang, "Efficiency and reliability of one-hop broadcasting in vehicular ad hoc networks," *IEEE Journal on Selected Areas in Communications,* vol. 29, pp. 151-160, 2011.

[90] C. Sommer, O. K. Tonguz, and F. Dressler, "Traffic information systems: efficient message dissemination via adaptive beaconing," *IEEE Communications Magazine,* vol. 49, pp. 173-179, 2011.

[91] R. K. Schmidt, T. Leinmuller, E. Schoch, F. Kargl, and G. Schafer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE network,* vol. 24, 2010.

[92] L. Fu, S. C. Liew, and J. Huang, "Effective carrier sensing in CSMA networks under cumulative interference," *IEEE Transactions on Mobile Computing,* vol. 12, pp. 748-760, 2013.

[93] C.-W. Hsu, C.-H. Hsu, and H.-R. Tseng, "MAC channel congestion control mechanism in IEEE 802.11 p/WAVE vehicle networks," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, 2011, pp. 1-5.

[94] R. Stanica, E. Chaput, and A.-L. Beylot, "Congestion control in CSMA-based vehicular networks: Do not forget the carrier sensing," in *Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2012 9th Annual IEEE Communications Society Conference on*, 2012, pp. 650-658.

[95] M. Barradi, A. S. Hafid, and J. R. Gallardo, "Establishing strict priorities in IEEE 802.11 p WAVE vehicular networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1-6.

[96] M. Artimy, "Local density estimation and dynamic transmission-range assignment in vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems,* vol. 8, pp. 400-412, 2007.

[97] M. Torrent-Moreno, P. Santi, and H. Hartenstein, "Distributed fair transmit power adjustment for vehicular ad hoc networks," in *Sensor and Ad Hoc Communications and Networks, 2006. SECON'06. 2006 3rd Annual IEEE Communications Society on*, 2006, pp. 479-488.

[98] Y. P. Fallah, C. Huang, R. Sengupta, and H. Krishnan, "Congestion control based on channel occupancy in vehicular broadcast networks," in *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*, 2010, pp. 1-5.

[99] P. K. Sahu, A. Hafid, and S. Cherkaoui, "Congestion control in vehicular networks using network coding," in *Communications (ICC), 2014 IEEE International Conference on*, 2014, pp. 2736-2741.

[100] M. S. Bouassida and M. Shawky, "A cooperative congestion control approach within VANETs: formal verification and performance evaluation," *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 11, 2010.

[101] Y. Gui and E. Chan, "Data scheduling for multi-item requests in vehicle-roadside data access with motion prediction based workload transfer," in *2012 26th International Conference on Advanced Information Networking and Applications Workshops*, 2012, pp. 569-574.

[102] V. Kumar and N. Chand, "Data scheduling in VANETs: A review," *International Journal of Computer Science and Communication*, vol. 1, pp. 399-403, 2010.

[103] L. Liu, W. Xia, and L. Shen, "An adaptive multi-channel MAC protocol with dynamic interval division in vehicular environment," in *Information Science and Engineering (ICISE), 2009 1st International Conference on*, 2009, pp. 2534-2537.

[104] S.-K. Lee and H.-K. Choi, "A study of variable interval for WAVE multi-channel access," in *Information and Communication Technology Convergence (ICTC), 2016 International Conference on*, 2016, pp. 1146-1148.

[105] S. Chantaraskul, K. Chaitien, A. Nirapai, and C. Tanwongvarl, "Safety communication based adaptive multi-channel assignment for vanets," *Wireless Personal Communications*, vol. 94, pp. 83-98, 2017.

[106] C. Han, M. Dianati, R. Tafazolli, X. Liu, and X. Shen, "A novel distributed asynchronous multichannel MAC scheme for large-scale vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 61, pp. 3125-3138, 2012.

[107] L. Zhang, Z. Liu, R. Zou, J. Guo, and Y. Liu, "A scalable CSMA and self-organizing TDMA MAC for IEEE 802.11 p/1609. x in VANETs," *Wireless Personal Communications*, vol. 74, pp. 1197-1212, 2014.

[108] D. B. Rawat, D. C. Popescu, G. Yan, and S. Olariu, "Enhancing VANET performance by joint adaptation of transmission power and contention window size," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, pp. 1528-1535, 2011.

[109] M. Sepulcre, J. Gozalvez, J. Härri, and H. Hartenstein, "Contextual Communications Congestion Control for Cooperative Vehicular Networks," *IEEE Trans. Wireless Communications,* vol. 10, pp. 385-389, 2011.

[110] N. Taherkhani and S. Pierre, "Congestion control in vehicular ad hoc networks using meta-heuristic techniques," in *Proceedings of the second ACM international symposium on Design and analysis of intelligent vehicular networks and applications*, 2012, pp. 47-54.

[111] W. Guan, J. He, C. Ma, Z. Tang, and Y. Li, "Adaptive message rate control of infrastructured DSRC vehicle networks for coexisting road safety and non-safety applications," *International Journal of Distributed Sensor Networks,* vol. 8, p. 134238, 2012.

[112] R. Baldessari, D. Scanferla, L. Le, W. Zhang, and A. Festag, "Joining forces for vanets: A combined transmit power and rate control algorithm," in *6th international workshop on intelligent transportation (WIT)*, 2010.

[113] C.-L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishnan, "Adaptive intervehicle communication control for cooperative safety systems," *IEEE network*, vol. 24, 2010.

[114] K. N. Qureshi, A. H. Abdullah, O. Kaiwartya, S. Iqbal, R. A. Butt, and F. Bashir, "A Dynamic Congestion Control Scheme for safety applications in vehicular ad hoc networks," *Computers & Electrical Engineering,* 2017.

[115] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated throughput analysis of IEEE 802.11 in presence of non ideal transmission channel and capture effects," *IEEE Transactions on Wireless Communications,* vol. 7, pp. 1276-1286, 2008.

[116] D. Malone, K. Duffy, and D. Leith, "Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions," *IEEE/ACM Transactions on Networking (TON),* vol. 15, pp. 159-172, 2007.

[117] K. Duffy and A. J. Ganesh, "Modeling the impact of buffering on 802.11," *IEEE Communications Letters,* vol. 11, 2007.

[118] W. Dong, W. Zhang, X. Chen, and G. Wei, "A new load equation for 802.11 MAC performance evaluation under non-saturated conditions," in *Communications in China (ICCC), 2012 1st IEEE International Conference on*, 2012, pp. 428-432.

[119] IEEE Standard for Telecommunications and Information Exchange Between Systems—LAN/MAN Specific Requirements—Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: High Speed Physical Layer in the 5 GHz Band, IEEE Standard 802.11a-1999, 1999.

[120] N. Taherkhani and S. Pierre, "Centralized and localized data congestion control strategy for vehicular ad hoc networks using a machine learning clustering algorithm," *IEEE Transactions on Intelligent Transportation Systems,* vol. 17, pp. 3275-3285, 2016.

[121] T. S. Rappaport, *Wireless communications: principles and practice* vol. 2: prentice hall PTR New Jersey, 1996.

[122] D. J. Deng, B. Li, L. Huang, C. H. Ke, and Y. M. Huang, "Saturation throughput analysis of multi- rate IEEE 802.11 wireless networks," *Wireless Communications and Mobile Computing*, vol. 9, pp. 1102-1112, 2009.

[123] Q. Ni, T. Li, T. Turletti, and Y. Xiao, "Saturation throughput analysis of error-prone 802.11 wireless networks," *Wireless Communications and Mobile Computing*, vol. 5, pp. 945-956, 2005.

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## LIST OF PUBLICATIONS

### International Refereed Journals

A. A. Almohammedi, N. K. Noordin, A. Sali, F. Hashim, W. A. Jabbar, and S. Saeed, "Modeling and analysis of IEEE 1609.4 MAC in the presence of error-prone channels," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, pp. 3531-3541, 2019.

A. A. Almohammedi, N. K. Noordin, A. Sali, F. Hashim, and M. Balfaqih, "An Adaptive Multi-Channel Assignment and Coordination Scheme for IEEE 802.11 P/1609.4 in Vehicular Ad-Hoc Networks," IEEE Access, vol. 6, pp. 2781-2802, 2018.

A. A. Almohammedi, N. K. Noordin, A. Sali, F. Hashim, and S. Saeed, "A Comprehensive Performance Analysis of the IEEE 802.11p based MAC for Vehicular Communications Under Non-saturated Conditions," *Journal of ICT Research and Applications*, vol. 11, pp. 92-113, 2017.

A. A. Almohammedi, N. K. Noordin, A. Sali, F. Hashim, and A. Al-Hemyari, "An Accurate Performance Analysis of Hybrid Efficient and Reliable MAC Protocol in VANET under Non-saturated Conditions," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 7, p. 999-1011, 2017.

A. A. Almohammedi, N. K. Noordin, and S. Saeed, "Evaluating the Impact of Transmission Range on the Performance of VANET," *International Journal of Electrical and Computer Engineering*, vol. 6, p. 800-809, 2016.