REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGNING AND PERFORMANCE ANALYSIS OF EFFICIENT AND RELIABLE MEDIUM ACCESS CONTROL PROTOCOLS FOR VEHICULAR AD HOC NETWORKS

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Signature

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Dedicated to my family

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Yildiz Technical University is one of the seven government universities situated in Istanbul besides being the 3rd oldest university of Turkey with its history dating back to 1911. It is regarded as one of the best universities in the country as well. I am happy and proud as a student of such renowned university.

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I hope that this thesis would be helpful to researchers working on PHY and MAC layers in VANETs.

A. F. M. Shahen SHAH

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LIST OF SYMBOLS

b_c	Backoff counter value
b_s	Backoff stage value
c	Speed of light
C_A	Number of cooperation attempts
C_{ch}	Channel condition
CW	Contention window size
d	Distance
D_T	Traffic density
$D_{vehicle}$	Legal distance between vehicles
$E[D]$	Average delay
$E[P_{drop}]$	Mean number of dropped packets relative to a successful transmission
$E[T_{drop}]$	Average duration to drop a packet
$E[T_{interval}]$	Average interval between two successfully received packets at one receiver
$E[X_{drop}]$	Average number of slot times for a dropped packet
f	Carrier frequency
f_{dop}	Doppler shift
G_r	Antenna gain for the receiver
$g(S_f)$	Processing gain of the correlation receiver
G_t	Antenna gain for the transmitter
h	Number of helpers
j	Number of clusters
J_T	Traffic jam intensity
L	Packet size

L_h	MAC and PHY header lengths
L_r	Length of road segment
$L_{vehicle}$	Length of vehicle
m_r	Maximum retransmission limit
N	Number of vehicles
n_L	Number of lanes in the road
O	Overhead
P_b	Probability of channel busy
P_c	Probability of collision
P_{cap}	Probability of frame capture
P_{d-CT}	Cooperation decision probability
P_{ef}	Probability of errored frame
P_{fdrop}	Probability that a packet is finally dropped
P_h	Probability of not getting helper
P_i	Channel idle probability
P_{outage}	Outage probability
$P_{parrival}$	Probability of packet arrival
P_{R_i}	Probability of i interfering frames originated from contending vehicles in the time slot
P_s	Probability of successful transmission
P_t	Probability of a packet transmission in a random slot time
P_{us}	Unsuccessful transmission probability
r_t	Transmission range
R_c	Control packet transmission rate
R_d	Data transmission rate
S	Throughput
S_f	Spreading factor
T_{AIFS}	Period of AIFS
T_c	Period of collided transmission

T_{coh}	Coherence time
T_{delay}	Propagation delay
T_{DIFS}	Period of DIFS
T_e	Expected period of a vehicle in a Markov state
T_s	Period of successful transmission
T_{SIFS}	Period of SIFS
T_{slot}	Period of slot
x	Average number of vehicles in the cluster
y	Average number of CMs
v	Vehicle velocity
z_o	Capture ratio
λ	Mean packet arrival rate
$\lambda_{vehicle}$	Mean arrival rate of vehicles to transmission range
σ_N	Power of background noise
σ_R	Local mean power of the transmitted frame at the receiver
α	Path loss exponent
β	Vehicle density
γ	SINR
γ_{th}	Threshold value of SINR

LIST OF ABBREVIATIONS

AC	Access category
ACK	Acknowledgment
AIFS	Arbitration inter-frame space
AIFSN	Arbitration inter-frame space number
AP	Access point
AV	Autonomous vehicles
BER	Bit error rate
BPSK	Binary phase shift keying
BSS	Basic service set
CB-MAC	Cluster-based MAC
CCH	Control channel
CDF	Cumulative distribution function
CH	Cluster head
CM	Cluster member
CMI	Cluster member information
CSMA/CA	Carrier sense multiple access with collision avoidance
CT	Cooperative transmission
CTS	Clear to send
CW	Contention window
CWSA	Cooperative WAVE service advertisement
DCF	Distributed coordination function
DIFS	DCF inter frame space
DS	Distribution system

DSRC	Dedicated short range communication
DSSS	Direct sequence spread spectrum
DT	Direct transmission
EDCA	Enhanced distributed channel access
EDCAF	Enhanced distributed channel access function
ESS	Extended service set
FIFO	First-in first-out
FSM	Finite state machine
GPS	Global positioning system
IEEE	Institute of electrical and electronics engineers
ITS	Intelligent transportation system
KTH	Keen to help
LAN	Local area networks
MAC	Medium access control
MGF	Moment-generating function
NACK	Negative acknowledgment
nsd	Non-safety data
PDF	Probability density function
PDR	Packet dropping rate
PHY	Physical
PSID	Provider service identifier
PSK	Phase-shift keying
QAM	Quadrature amplitude modulation
QoS	Quality of service
RCIM	Request to cluster merging
RECV-MAC	Reliable and efficient cooperative MAC
ReTCI	Registration to cluster
RTCF	Request to cluster formation
RTS	Request to send

SCH	Service channel
SER	Symbol error rate
SHM	Selected helper message
SIFS	Short inter-frame space
SINR	Signal-to-interference-plus-noise ratio
sm	Safety messages
STA	Station
TDMA	Time-division multiple-access
UML	Unified modeling language
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VANET	Vehicular ad hoc network
WAVE	Wireless access in vehicular environments
WSA	WAVE service advertisement
WTI	Willing to involve

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ABSTRACT

Designing and Performance Analysis of Efficient and Reliable Medium Access Control Protocols for Vehicular Ad Hoc Networks

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Doctor of Philosophy Thesis

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Vehicular ad hoc networks (VANETs) have recently attracted interest for automation and intelligent transportation system (ITS). VANETs increase transportation efficiency and road safety. VANETs comprise inter-vehicle communication (V2V, vehicle-to-vehicle) as well as communication between vehicle and infrastructure (V2I, vehicle-to-infrastructure). VANETs facilitate numerous applications which can be categorized as safety messages (sm) and non-safety data (nsd). However, to have useful applications the communication between vehicles and with existing networking infrastructures should be efficient. For any ad hoc network, medium access control (MAC) protocol is one of the most significant parts, because efficient and reliable data transmission directly depends on MAC protocol.

The IEEE 802.11p standard is outlined by the institute of electrical and electronics engineers (IEEE) to support wireless access in vehicular environments (WAVE) and to provide MAC and Physical (PHY) Layer specifications for VANETs. Later IEEE 802.11 standard incorporated IEEE 802.11p. In IEEE 802.11p and IEEE 802.11, distributed coordination function (DCF) is the fundamental mechanism to access the medium and enhanced distributed channel access function (EDCAF) is sketched to support contention-based prioritized Quality of Service (QoS) at MAC layer. In this thesis, the performance of DCF and EDCAF for both IEEE 802.11p and IEEE 802.11 is modeled and analyzed. An analytical analysis based on Markov chain model is presented. The derived performance model is justified by numerical results. Then we investigated the

influence of channel fading and capture effect. Nakagami, Rayleigh, and Rician faded channels are considered. However, both IEEE 802.11p and IEEE 802.11 can not fulfill the performance criteria of VANETs.

In VANETs, high mobility and relative mobility among vehicles can result in rapid topology changes with frequent link breakage and unstable communications which cause collision and packet loss. Alternatively, clustering VANETs into small groups which limits channel contention and controls the network topology efficiently. In this thesis, a novel cluster-based MAC (CB-MAC) protocol is proposed for VANETs. The cluster formation process is defined. Moreover, cluster head (CH) election and cluster merging processes are described for efficient communication in the cluster as well as out of the cluster. The mechanism defined in IEEE 802.11 is specially designed for only direct communications and is not suitable for cluster-based communications. Therefore, new control packets are introduced and the existing control packet format is modified to support cluster-based communications. For effective MAC protocol design, the request to send (RTS)/ clear to send (CTS) mechanism is not used for sm which are of broadcast nature. On the other hand, the RTS/CTS mechanism is used for nsd delivery to eliminate hidden node problem. Markov chain model based analytical model is presented to explore the performance of proposed CB-MAC protocol. The proposed protocol is validated by numerical studies. The numerical results exhibit that the proposed CB-MAC protocol improves system performance and satisfies the delay constraint of 100 ms for sm.

Another way, cooperative transmission can improve the communication reliability and can enhance communication rate with lower delay by alleviating wireless channel impairments caused by the mobility in VANETs. In this thesis, a novel reliable and efficient cooperative MAC protocol for VANETs (RECV-MAC) is also proposed which is designed both for sm and nsd transmission. RECV-MAC ensures reliable and efficient transmission with the help of helpers which have good channel condition to both the sender and the receiver. New control messages are introduced to support cooperative communication. The mechanism is defined to choose the suitable transmission mode as well as to select the optimal helper. To investigate the performance of the proposed RECV-MAC protocol, Markov chain model based analytical analysis is provided. The proposed RECV-MAC protocol is validated by numerical studies. The performance of the RECV-MAC protocol is compared with the traditional MAC model which is based on the IEEE 802.11p and a quantitative comparison with existing cooperative MAC schemes is presented. It is obvious from the comparison that the RECV-MAC performs better than IEEE 802.11p and existing cooperative MAC schemes. The numerical results demonstrate that the RECV-MAC protocol improves the performance with higher throughput, enhances reliability of communication by decreasing PDR, and

decreases delay, in particular, satisfies the delay constraint of 100 ms for sm.

The performance of IEEE 802.11p, IEEE 802.11, and CB-MAC is optimized. Performance optimization mechanism is presented. The comparison between IEEE 802.11p and IEEE 802.11is provided. The microscopic mobility model is generated in SUMO for practical scenario. Monte Carlo simulation results are presented which verify analytical analysis. Complexity analysis is presented. Comparison between complexity analysis is illustrated.

Keywords: IEEE 802.11, IEEE 802.11p, MAC, optimization, VANETs

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ÖZET

Araçsal Tasarsız Ağlar için Verimli ve Güvenilir Ortam Erişim Kontrol Protokollerinin Tasarımı ve Performans Analizi

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Araçsal tasarsız ağlar (VANET'ler) son zamanlarda otomasyon ve akıllı ulaşım sistemine (ITS) ilgi duymaktadır. VANET'ler nakliye verimliliğini ve yol güvenliğini arttırmaktadır. VANET'ler araç ile araç iletişimi (V2V, araç-araç) ve araç ile altyapı (V2I, araç-altyapı) arasındaki iletişimi içerir. VANET'ler güvenlik mesajları (sm) ve güvenlik dışı veriler (nsd) olarak sınıflandırılabilecek sayısız uygulamayı kolaylaştırır. Bununla birlikte, faydalı uygulamalara sahip olmak için araçlar ile mevcut ağ altyapıları arasındaki iletişim verimli olmalıdır. Herhangi bir tasarsız (ad hoc) ağ için, ortam erişim kontrolü (MAC) protokolü en önemli bölümlerden biridir, çünkü verimli ve güvenilir veri iletimi doğrudan MAC protokolüne bağlıdır.

IEEE 802.11p standardı, IEEE tarafından araç ortamlarındaki (WAVE) kablosuz erişimi desteklemek ve VANET'ler için MAC ve Fiziksel (PHY) Katman özelliklerini sağlamak için ana hatlarıyla belirtilmiştir. Daha sonra IEEE 802.11 standardı, IEEE 802.11p'yi içermekteydi. IEEE 802.11p ve IEEE 802.11'de, dağıtılmış koordinasyon fonksiyonu (DCF) orta ve gelişmiş dağıtılmış kanal erişim fonksiyonuna (EDCAF) erişmek için temel mekanizmadır ve MAC katmanındaki çekişmeli öncelikli Servis Kalitesi (QoS) desteği için tasarlanmıştır. Bu tez çalışmasında, hem IEEE 802.11p hem de IEEE 802.11 için DCF ve EDCAF performansı modellenmiş ve analiz edilmiştir. Markov zincir modeline dayanan analitik bir analiz sunulmuştur. Türetilmiş performans modeli sayısal sonuçlarla doğrulanmıştır. Sonra kanal sönümlemesi ve yakalama etkisinin etkisini araştırılmıştır. Nakagami, Rayleigh ve Rician sönümlemeli kanallar

göz önünde bulundurulmuştur. Ancak, hem IEEE 802.11p hem de IEEE 802.11, VANET'lerin performans kriterlerini yerine getirememektedir.

VANET'lerde, araçlar arasında yüksek ve göreceli hareketlilik, sık bağlantı kopması, çarpışma ve paket kaybına neden olan dengesiz iletişim ile hızlı topoloji değişikliklerine neden olabilir. Alternatif olarak, VANET'lerin kanal çekişmesini sınırlayan ve ağ topolojisini verimli bir şekilde kontrol eden küçük gruplar halinde kümeleme yapılabilir. Bu tezde, VANET'ler için kümelemeye dayalı yeni bir MAC (CB-MAC) protokolü önerilmiştir. Küme oluşum süreci tanımlanmıştır. Ayrıca, küme içi ve küme dışında verimli iletişim için küme başı (cluster head, CH) seçimi ve küme birleştirme işlemleri açıklanmaktadır. IEEE 802.11'de tanımlanan mekanizma, sadece doğrudan iletişim için özel olarak tasarlanmış ve küme tabanlı iletişim için uygun değildir. Bu nedenle, yeni kontrol paketleri tanıtılmakta ve mevcut kontrol paketi formatı küme tabanlı iletişimi desteklemek için değiştirilmektedir. Etkili MAC protokolü tasarımı için gönderme niteliğinde olan sm için gönderme isteği (RTS) / göndermeye hazır (CTS) mekanizması kullanılmaz. Öte yandan, RTS / CTS mekanizması nsd teslimi için gizli düğüm problemini ortadan kaldırmak için kullanılır. Önerilen CB-MAC protokolünün performansını incelemek için Markov zincir modeline dayalı analitik model sunulmuştur. Önerilen protokol, sayısal çalışmalar ile doğrulanmıştır. Sayısal sonuçlar, önerilen CB-MAC protokolünün sistem performansını iyileştirdiğini ve sm için 100 ms'lik gecikme kısıtlamasını sağladığını göstermektedir.

Diğer taraftan, işbirliğine dayalı iletim, VANET'lerdeki hareketliliğin neden olduğu kablosuz kanal bozulmalarını hafifleterek iletişim güvenilirliğini artırabilir ve düşük gecikmeli iletişim hızını artırabilir. Bu tez çalışmasında, VANET'ler (RECV-MAC) için hem sm hem de nsd iletimi için tasarlanmış yeni ve güvenilir bir işbirlikli MAC protokolü önerilmiştir. RECV-MAC, hem göndericiye hem de alıcıya iyi kanal koşulu olan yardımcıların yardımıyla güvenilir ve verimli iletim sağlar. İşbirliğine dayalı iletişimi desteklemek için yeni kontrol mesajları tanıtılmıştır. Mekanizma uygun aktarım modunu seçmek ve en uygun yardımcıyı seçmek için tanımlanmıştır. Önerilen RECV-MAC protokolünün performansını araştırmak için Markov zincir modeline dayalı analitik analiz yapılmıştır. Önerilen RECV-MAC protokolü, sayısal çalışmalar ile doğrulanmıştır. RECV-MAC protokolünün performansı, IEEE 802.11p'yi temel alan geleneksel MAC modeliyle karşılaştırılıp ve mevcut işbirlikli MAC şemalarıyla performans açısından karşılaştırılmıştır. Karşılaştırmada, RECV-MAC'in IEEE 802.11p ve mevcut işbirlikli MAC şemalarından daha iyi performans gösterdiği açıktır. Sayısal sonuçlar, RECV-MAC protokolünün performansı daha yüksek verimlilikle geliştirdiğini, PDR'yi azaltarak iletişimin güvenilirliğini arttırdığını ve özellikle de gecikmeyi azalttığını, özellikle sm için 100 ms'lik gecikme sınırını karşıladığını göstermektedir.

IEEE 802.11p, IEEE 802.11 ve CB-MAC'in performansı optimize edilmiş ve performans optimizasyon mekanizmaları sunulmuştur. IEEE 802.11p ve IEEE 802.11 arasındaki karşılaştırma sağlanmıştır. Mikroskopik mobilite modeli pratik senaryo için SUMO'da üretilmiştir. Analitik analizi doğrulayan Monte Carlo simülasyon sonuçları sunulmuştur. Ayrıca, karmaşıklık analizi sunulmuş ve karmaşıklık analizi arasındaki karşılaştırma gösterilmiştir.

Anahtar Kelimeler: IEEE 802.11, IEEE 802.11p, MAC, optimizasyon, VANET

1
Introduction

1.1 Literature Review

Recently, vehicular ad hoc networks (VANETs) have garnered much attention for automation and intelligent transportation system (ITS). VANET is a significant element of ITS, which supports numerous applications such as congestion alleviation, safety, security, comfort and convenience, productivity and operational efficiency, environment monitoring and protection etc. VANETs increase transportation efficiency and road safety. VANETs make the deployment of autonomous vehicles (AVs) easier and faster by reducing expensive sensor dependence. VANETs comprise inter-vehicle communication (V2V, vehicle-to-vehicle) as well as communication between vehicle and infrastructure (V2I, vehicle-to-infrastructure). A palpable example is presented in Figure 1.1.

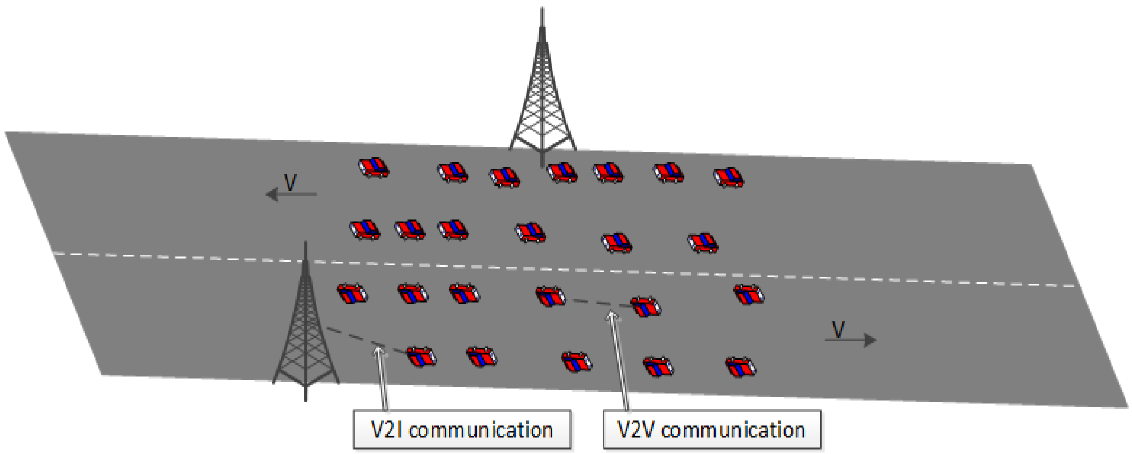

Figure 1.1 Vehicular ad hoc network (VANET)

VANETs facilitate numerous applications which can be categorized as safety messages (sm) and non-safety data (nsd). Emergency warning, accident prevention, road condition, lane-changing assistant, emergency electronic brake light indication, traffic sign or signal violation warning etc. include safety messages and traffic information system, map update, weather information, web browsing, content distribution, gas station or restaurant location and price information, gaming etc. include non-safety data. However, to have useful applications the communication between vehicles and with existing networking infrastructures should be efficient.

The IEEE 802.11p standard [1] is outlined by the institute of electrical and electronics engineers (IEEE) to support wireless access in vehicular environments (WAVE) and to define medium access control (MAC) and physical (PHY) Layer specifications for VANETs. A 75 MHz wide spectrum in 5.850-5.925 GHz band is assigned for the Dedicated Short Range Communication (DSRC) with seven 10 MHz wide channels, one channel is control channel (CCH) and six are service channels (SCHs). Later IEEE 802.11 [2] incorporated the IEEE 802.11p. In the 802.11 standard, distributed coordination function (DCF) is the fundamental mechanism to access the medium and the enhanced distributed channel access function (EDCAF) is sketched to support contention-based prioritized Quality of Service (QoS). To ensure QoS, EDCAF outlines four access categories (ACs) with different parameters to contend for the transmission. QoS support is very important for designing useful and popular VANETs MAC protocols. Moreover, QoS varies for different applications due to the diversity in requirements. A MAC protocol should provide precise traffic differentiation and support for heterogeneous services. DCF employs a carrier-sense multiple access with collision avoidance (CSMA/CA) with binary exponential backoff algorithm. In addition, request to send (RTS)/ clear to send (CTS) handshake is designed to get rid of the hidden vehicular node problem.

The ITS G5 standard [3] has been drafted by the ETSI. In Europe, a 50 MHz wide spectrum in the frequency band of 5.875-5.925 GHz has been allocated by ETSI. The IEEE 1609.4 standard [4] controls the action of upper layer data transmissions through multiple channels, without PHY layer knowledge and defines the multi-channel operation, channel routing as well as switching for altered scenarios. According to IEEE 1609.4, the CCH is reserved for safety messages called beacons and control messages (i.e., service advertisement messages) and the SCHs are reserved for non-safety data. The period during which a vehicle stays tuned to the CCH and SCHs are referred to CCH and SCH interval, respectively. There is a guard time because of radio switching delay and time synchronization error at the beginning of all intervals. Vehicles have to tune to the identical channel at the exact time to establish correspondence with each other and for data transmission among them. There are certain requirements to fulfill the performance criteria for VANETs, such as for safety messages strict delay constraint is 100 ms [5–7].

The IEEE 802.11 includes four basic physical elements: wireless media, distribution system (DS), access point (AP) and station (STA) as in Figure 1.2. DS is the system used to combine the local area networks (LAN) and the basic service set (BSS). To create an extended service set (ESS), more than one BSS is required. The addressable unit is a station (STA) which is wireless communication device. Wireless LANs without an AP are called ad hoc networks.

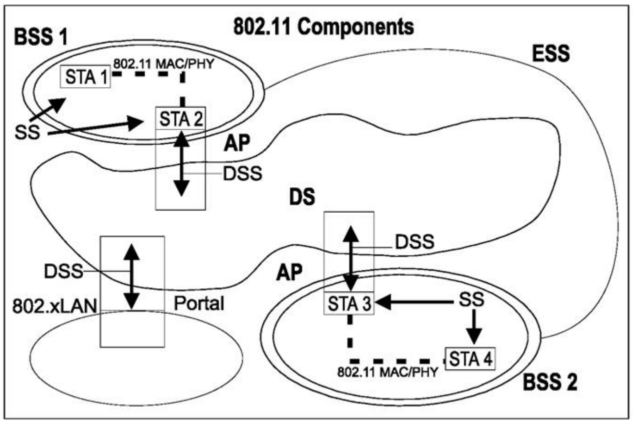

Figure 1.2 IEEE 802.11 architecture

The BSS is an infrastructure that includes a number of mobile stations (STAs) i.e. vehicles. The basic access system is DCF which is based on CSMA/CA. In addition, RTS/ CTS handshake is used to get rid of the hidden vehicular node problem. For any ad hoc network, MAC protocol is one of the most significant parts, because efficient and reliable data transmission directly depends on MAC protocol.

Performance analysis of the IEEE 802.11p protocol for VANETs is carried out in [8–17]. In [8–14], only safety messages are considered and only non-safety data is considered in [15–17]. Moreover, mobility is not considered in [8–17]. The impact of IEEE 802.11p EDCAF is studied in [8, 15, 18–20]. In [15], backoff counter freezing is not considered and authors assumed that backoff counter will be decreased regardless of channel state. All four ACs is not included in studies, for example, one, two, or three ACs are taken into account in [8, 18, 20]. In [8], internal collision is not taken into account as well as throughput expression is not presented in [19]. In [20], model and study include some parameters which are not in IEEE 801.11p such as acknowledgment, retransmission limit, etc. Therefore, developing more accurate performance model is essential that will consider all major factors which may influence the performance.

An ideal transmission channel is assumed in all of these models where it is taken into account that a transmitted packet is received successfully if no collision happens or a transmitted packet is lost because of collision. In reality, because of shadowing, fading, and multipath propagation, a transmitted signal reaches the receiver with different power levels. Although there is no collision, a transmitted packet may be lost because of decoding error under these effects [21]. On the other hand, a transmitted packet can be received successfully at the receiver when a collision occurs due to capture effect. The packet with highest power at the receiver can be received successfully for concurrent transmissions [21]. There are three fading channels which are given below:

In cases where there is no direct vision (LoS) between the transmitter and the receiver and the received signal is composed of multipath components which are reflected only from the environment, the envelope of the received signal is Rayleigh distributed. This kind of channel is called Rayleigh fading channel. The probability density function (pdf) of Rayleigh fading is given as

$$f_Y(y) = \frac{y}{\sigma_R^2} e^{-\frac{2}{2\sigma_R^2}}. \quad y \geq 0 \tag{1.1}$$

Here, σ^2 is the variance of the orthogonal Gaussian components that make up the Rayleigh variable. The expected value for this distribution is $m_R = E[Y]\sqrt{\pi/2}\sigma_R$, mean power $\Omega = E[Y^2] = 2\sigma_R^2$ and variance $\sigma_R^2 = (2-\pi/2)\sigma^2$. The cdf of the Rayleigh distribution is

$$F_Y(y) = \int_{-\infty}^{y} f_Y(u)du = \int_{-\infty}^{y} \frac{u}{{\sigma_R}^2} e^{-\frac{u^2}{2\sigma^2}} du = 1 - e^{-\frac{y^2}{2{\sigma_R}^2}}. \quad y \geq 0 \tag{1.2}$$

When the LoS component is present between the transmitter and the receiver and the multi-path components reach the receiver, the envelope of the received signal is Rician distributed and the channel is called the Rician fading channel. The pdf of the Rician distribution is given as

$$f_Y(y) = \frac{y}{{\sigma_R}^2} e^{-\frac{y^2+s^2}{2{\sigma_R}^2}} I_0\left(\frac{ys}{{\sigma_R}^2}\right). \quad y \geq 0 \tag{1.3}$$

Here, the zero-order Bessel function of the first type $I_0(.)$ represents the envelope component from the constant propagation path of the received signal s. The Rician parameter is defined as $K = P_{tr}/P_y$, with $P_{tr} = s^2$ the power of the signal directly reaching the transmitter from the transmitter and $P_y = 2\sigma_R^2$, the power of the signal reaching the transmitter from the transmitter to the receiver. In this case, the pdf of the Rician distribution linked to K is

$$f_Y(y) = 2y(1+K)\frac{y}{{\sigma_R}^2} e^{-K-y^2(1+K)} I_0\left(2y\sqrt{K(1+K)}\right). \quad y \geq 0 \tag{1.4}$$

In the Rayleigh fading channel obtained with $K = 0$, the transmitter and receiver do not see each other and all components are reflected and reach the receiver. Since the advantage of a system depends on its success under the worst conditions, the error performance of communication systems is mostly examined in Rayleigh fading channel.

The Nakagami-m distribution includes the Rayleigh and Rician distributions. The probability density function of the Nakagami-m distribution forms the basis of the central chi-square distribution. The m value here is the fading parameter of Nakagami-m and ranges from 0.5 to ∞. The pdf of the Nakagami distribution is like

$$f_Y(y) = \frac{1}{y\Gamma(m)} e^{\left(-\frac{my\sigma_{Noise}}{\sigma_R \Omega}\right)} \left(\frac{my\sigma_{Noise}}{\sigma_R \Omega}\right)^m, \quad y \geq 0 \tag{1.5}$$

where $\Gamma(m)$ is the Gamma function, where $\Omega = E[Y^2]$. Nakagami-m gives one-way Gaussian distribution when $m = 0.5$ and Rayleigh distribution when $m = 1$. When $m \rightarrow \infty$, the Nakagami-m fading channel converges to the non-fading AWGN channel.

Nakagami-m distribution is approximately related to Rician distribution according to the values taken by m. Accordingly, the relationship between Rician parameter K and m can be written as

$$K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}}. \tag{1.6}$$

Performance exploration of the IEEE 802.11 protocol for VANETs is carried out in [22–27]. In [22–24], only safety messages are considered and only non-safety data is considered in [25–27]. However, IEEE 802.11 can not meet the criteria for VANETs due to high channel contention, rapid network topology changes because of mobility, etc. Clustering reduces delay by limiting channel contention, controls network topology efficiently, and increases handover success rate [28]. The impact of IEEE 802.11 DCF and IEEE 802.11 EDCAF are provided in [24, 26, 27, 29–32] and in [16, 33–36], respectively. The impact of cluster design on communication quality is provided in [28]. In [28], authors demonstrate that the performance of VANETs depends on cluster size, vehicle velocity, traffic demand and contention window size. However, no RTS/CTS packets are exchanged before data transmission in [28]. For this reason, data transmission in [28] is effected by the hidden terminal problem and performance decreases. A cooperative cluster-based MAC protocol named as CCB-MAC is proposed for VANET in [37]. CCB-MAC protocol is proposed for sm only and CCB-MAC protocol is offered based on time-division multiple-access (TDMA). In [38], a multi-channel cooperative clustering-based MAC protocol is proposed to increase the reliability of transmission as well as support QoS for different applications in VANETs which is TDMA based. Besides, this protocol suffers from hidden node terminal problem.

During unreserved time slots, even if the channel is idle, the sender awaits for the next frame for retransmission upon a failure tran[39], a hybrid cluster-based MAC protocol for VANETs is suggested to facilitate channel utilization and maintain network stability. CH is selected based on their motility factors. However, this protocol is proposed for safety messages only and it is based on TDMA schemes. In [40], a cluster-based multichannel MAC protocol for VANETs is proposed which is TDMA based. The TDMA based MAC protocols [9, 37, 39, 40] cannot utilize all the time slots of a frame due to lack of neighboring nodes in the network which wastes time slots. Consequently, TDMA MAC protocol is unsuccessful in utilizing the available resources. Moreover, data transmission or clustering is not possible if there is no idle slot. In [41], a MAC protocol is suggested for VANETs referred to as DMMAC. In [41], fuzzy-logic inference system (FIS) is used to forecast the future speeds as well as locations of all CMs. However, DMMAC protocol is proposed for only emergency messages. In [42], multihop-cluster-based hybrid architecture for VANET is proposed which is also for safety message dissemination only. In [43], cluster-based data download and forwarding method for VANETs is proposed. However, only throughput analysis is given but delay and PDR analysis are not provided. A comparative study of clustering techniques for VANET is provided in [44]. The IEEE 802.11 suffers from contention based random access scheme in high density network. Moreover, the RTS/ CTS method of the IEEE 802.11 is inoperative in broadcast mode since RTS/CTS mechanism requires CTS after RTS. Therefore, when the message is broadcast to all nodes, all nodes have to send CTS. Thus, simultaneous CTS transmission will cause more collisions [45]. Therefore, both the IEEE 802.11 and the existing cluster-based MAC methods are not free from packet dropping and throughput reduction. Besides, existing cluster-based mechanisms do not satisfy the strict delay requirement of 100 ms for sm. Furthermore, these existing cluster based works [37, 39, 41–43] provide a mechanism for only safety messages. Thus, an effective cluster based MAC protocol is needed for both safety messages and non-safety data transmission. Impact of mobility should be considered too [46].

Another way, cooperative communication [47] improves transmission performance with the assistance of neighboring nodes. Cooperative communication can enhance the reliability of communications in VANETs by mitigating impairments due to user mobility and to improve communication quality with higher throughput and lower delay, in particular, safety messages should not experience delay more than 100 ms as stated in [5–7, 48]. The impact of IEEE 802.11 based VANETs and throughput analysis for unicast transmission is provided in [49]. Mobility model for VANETs is presented in [50]. The impact of IEEE 802.11p in VANETs is explored in [9, 15, 51, 52]. The impact of IEEE 802.11p EDCA method is investigated in [10, 20, 53]. Designing MAC protocol is challenging for VANETs because of high mobility which changes topology promptly [54]. Alternatively, cooperative communication can improve the communication reliability. CCB-MAC which is a cooperative clustering based MAC protocol for VANET is suggested in [37]. CCB-MAC considered only safety messages. However, if there is no idle slot, cooperation is not possible. In [55], a cooperative MAC protocol named ADC-MAC is recommended for VANETs which is based on IEEE 802.11. ADC-MAC uses RTS/CTS access mechanism of the IEEE 802.11 which is inoperative for sm which are of broadcast nature. Since the RTS will be broadcast to all vehicular nodes, all vehicular nodes will send CTS which causes more collisions [48]. In [56], CAH-MAC is proposed for VANETs which is TDMA based cooperative MAC protocol. CAH-MAC supports point-to-point communication only, this protocol does not support broadcast or multicast modes of communication. In CAH-MAC, a vehicular node retains a list of its one-hop and two-hop nearby nodes for cooperation individually. Variations in traffic, channel circumstance, as well as network topology are numerous and normal in VANETs. Therefore, the information in the list may not appropriately reveal the existing channel state. In this situation, it is highly probable that the sender will not get helpers or helpers will be unsuccessful in executing cooperation which degrades throughput and causes delay in packet delivery. Moreover, in CAH-MAC, adjacent vehicular nodes cooperate by using unreserved time slots. Consequently, cooperation is not possible if there is no available time slot. In [57], an enhanced CAH-MAC is proposed to efficiently utilize a time slot by avoiding cooperation collisions. In [58], a cooperative MAC is proposed for safety messages in VANETs. A scheduling protocol based on centralized TDMA is proposed for VANETs in [59]. In [60], VeMAC is proposed for VANET which is also a TDMA based MAC protocol. The TDMA based MAC protocols may result in wastage of time slots due to VANETs dynamic topology. If there are inadequate nodes in the network to utilize all the time slots of a frame, then the wastage occurs. During unreserved time slots, though the channel is idle, the sender waits for the next frame for retransmission upon a failed transmission which causes high delay and low throughput in VeMAC. Moreover, these methodologies can be ineffective in utilizing the offered radio resources. The resource sharing problem in VANETs is investigated in [61, 62]. Message delivery technique of VeMAC for both periodic as well as event-driven safety messages is scrutinized in [63]. In [64], a novel cooperative MAC protocol is offered for safety messages in VANETs which does not satisfy the delay constraint. In [65], VC-MAC is provided for gateway downloading in VANETs. In [66], cooperative relay broadcasting (CRB) is introduced for vehicular networks where neighboring nodes rebroadcast the packet from the sender to increase the reliability of the broadcast. CRB choice is obtained proactively based on channel states. However, delay analysis is not provided in [56, 60, 65, 66]. In [67], a cooperative MAC protocol is proposed for VANETs which can not satisfy latency requirement of sm. In [68], a MAC protocol is suggested for VANETs which is IEEE 802.11 based cooperative MAC protocol that does not fulfill the delay requirement of safety messages. In [37, 56, 58, 60, 64], cooperative MAC is recommended for safety messages only, and mobility is not considered. In [68, 69], cooperative MAC protocol is suggested in VANETs for non-safety data only. A cooperative MAC is required both for safety messages and non-safety data to ensure communication quality with higher throughput, as well as reliable and efficient communication by decreasing PDR and delay.

1.2 Objective of the Thesis

In addition to various obstacles due to unreliable wireless transmission medium, development and operation of VANETs have some unique challenges when compared with other forms of wireless networks. High node mobility, relative mobility among vehicles, dynamic topology changes with frequent link breakage, and strict delay constraints of high priority safety messages are some common challenges in VANETs. In VANETs, high mobility and relative mobility among vehicles can result in rapid topology changes with frequent link breakage and unstable communications which cause collision and packet loss. Alternatively, cooperative transmission can improve the communication reliability and can enhance communication rate with lower delay by alleviating wireless channel impairments caused by the mobility in VANETs. Another way, clustering VANETs into small groups which limits channel contention and controls the network topology efficiently. The main objective of the thesis is to enhance the reliability of communications in VANETs by mitigating impairments due to user mobility and to improve communication quality with higher throughput and lower delay, in particular, safety messages should not experience delay more than 100 ms.

The contributions of this thesis is summarized as follows.

In Chapter 2, the impact of IEEE 802.11p DCF and EDCAF in VANETs is analyzed. Channel Fading and Capture Effect are considered. To assess the performance of the IEEE 802.11p MAC for VANETs, an analytical model based on Markov chain model is presented. The parameters that could impact performance are taken into consideration. The relationship among parameters and performance metrics are derived. Firstly, ideal channel condition is assumed. Later, the effect of capture and channel fading is studied. Nakagami, Rayleigh, and Rician faded channels are considered. Furthermore, to verify the analytical studies numerical results are presented and whether the IEEE 802.11p can fulfill the performance criteria for

VANETs or not is checked. A conference paper is published in IEEE International conference and a journal article is submitted to and currently under review in IEEE Transactions on Vehicular Technology, with this contribution.

In Chapter 3, the performance of IEEE 802.11 DCF and EDCAF are analyzed. Markov chain model based analytical model is developed where all key parameters that can affect the performance are taken into consideration. The relationship among performance metrics and MAC parameters are achieved. Numerical results are presented to scrutinize the performance of IEEE 802.11 MAC for VANETs and whether the IEEE 802.11 can fulfill the performance criteria for VANETs or not is checked. At first, we considered ideal channel and later channel fading and capture effect is taken into study. Four conference papers are published in IEEE International conferences and a book chapter is published by Springer, with this contribution.

In Chapter 4, a novel cluster-based MAC (CB-MAC) protocol for VANETs is proposed. The CB-MAC protocol is designed for both sm and nsd transmission. The cluster formation mechanism is defined. The procedure of joining as well as leaving the cluster is provided. Moreover, CH election process is described. The IEEE 802.11 standard supports only direct communication and is not designed for cluster-based communication. Hence, new control packets are introduced and the current control packet format is changed to support cluster-based communications. For effective MAC protocol design, RTS/CTS access technique is not used for sm, but the RTS/CTS mechanism is used for nsd transmission to abolish the hidden vehicular node problem. Markov chain model based analytical analysis of the proposed CB-MAC protocol is provided. Throughput, PDR, and delay expressions are obtained. Besides, overhead introduced by the CB-MAC protocol is considered. Moreover, the CB-MAC protocol is verified by numerical studies. The numerical results demonstrate that the CB-MAC protocol outperforms existing schemes under the same network scenarios and improves system performance as well as achieves objectives. QoS of CB-MAC protocol is ensured by the IEEE 802.11 EDCA mechanism. A journal article is published in IET Intelligent Transport Systems, and a book chapter is published by Springer, with this contribution.

In Chapter 5, a novel reliable and efficient cooperative MAC protocol is proposed for VANETs, referred to as RECV-MAC. Since a random access mechanism is the most suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. CSMA/CA which is used by the IEEE 802.11p. Therefore, the proposed RECV-MAC protocol is compatible with the IEEE 802.11p. New control messages are introduced to transmit safety messages and non-safety data such as Negative Acknowledgment (NACK), Keen To Help (KTH), Selected

Helper Message (SHM), Willing To Involve in the offered service (WTI), Cooperative WAVE Service Advertisement (CWSA) etc. As cooperation initiates complexity and signaling overhead, cooperation all the time may not be beneficial or even needed. Cooperation becomes superfluous when cooperation gain is negligible compared to cost. Therefore, a scheme is required to decide whether a packet should be transmitted directly or cooperatively. An algorithm is suggested to determine an appropriate transmission mode. The cooperation gain depends on the helper and for that optimal helper selection procedure is also provided. Overhead introduced by cooperative communication and vehicle mobility are considered. Markov Chain model based analytical analysis of the RECV-MAC protocol is provided. Finally, the RECV-MAC protocol is evaluated by numerical studies. Numerical results show that the RECV-MAC protocol enhances the performance and achieves objectives. QoS among different traffic classes is assured by implementing IEEE 802.11p EDCA mechanism in RECV-MAC protocol. A journal article is published in IET Communications, with this contribution.

In Chapter 6, the performance of IEEE 802.11p, IEEE 802.11 and CB-MAC protocol are optimized. Performance optimization mechanism is presented. The comparison between IEEE 802.11p and IEEE 802.11is provided. The microscopic mobility model is generated in SUMO for practical scenario. Monte Carlo simulation results are presented which verify analytical analysis. Complexity analysis of IEEE 802.11p, IEEE 802.11, CB-MAC protocol, and RECV-MAC protocol are given. Comparison between complexity analysis is illustrated. Two journal articles are submitted to and currently under review in IEEE Wireless Communications Letters, with this contribution.

1.3 Hypothesis

In order to have useful applications, communication between vehicles and existing networking infrastructures should be reliable and efficient. Cooperative communication can increase the communication link reliability by mitigating wireless channel impairments caused by mobility in VANETs. Cooperative communication improves transmission performance with the assistance of neighboring nodes. A helper node is a node among the neighboring nodes which relays packets to the receiver thanks to having a good channel condition to both the sender and receiver nodes. Due to the transmission nature of wireless communication, nearby stations can listen to the broadcast of a packet from the sender to the receiver. The overheard packet experiencing a bad channel state to the receiver can be relayed by a helper or helpers. Cooperative transmission can enhance the throughput of the whole network because of the reliability of a packet delivery with the help of helper. Another way, cluster-based communication can improve the reliability of communication by forming a cluster with adjacent vehicles moving in the same direction. For stable and reliable cluster design, different direction moving vehicles should form a different cluster. Otherwise, forming a cluster with different direction moving vehicles will create a lot of signaling overhead for re-clustering frequently. From each cluster, a cluster head (CH) will be chosen who will coordinate communication among cluster members (CMs) inside the cluster and to the outside through roadside gateways. CH works as the access point for all kind of inter-cluster communication and intra-cluster communication. CH also facilitates cluster formation and manages cluster membership. Medium access, traffic control and QoS provision within a cluster are managed by the CH. Over the wide VANETs, CHs can form the dynamic virtual backbone to manage crucial tasks, for instance channel allocation and routing at higher layers.

The rest of this thesis is organized as follows: performance modeling and analysis of the IEEE 802.11p and IEEE 802.11 are presented in Chapter 2 and Chapter 3, respectively. A Novel Cluster-Based MAC (CB-MAC) Protocol for VANETs is proposed in Chapter 4. A Novel Reliable and Efficient Cooperative MAC Protocol for VANETs (RECV-MAC) is provided in Chapter 5. Optimization and complexity analysis are presented in Chapter 6. Chapter 7 concludes and summarizes this dissertation.

2
Modeling and Performance Analysis of IEEE 802.11p

In this section, the IEEE 802.11p is modeled and performance is analyzed. The basic access system of IEEE 802.11p is distributed coordination function (DCF) and enhanced distributed channel access function (EDCAF) is sketched to differentiate priority and ensure QoS among different traffic classes. IEEE 802.11p DCF is presented in Section 2.2, Section 2.3 details out EDCAF, and Section 2.4 describes the performance under channel fading and capture effect.

2.1 Distributed Coordination Function

In this section, a systematic model is presented to scrutinize the impact of IEEE 802.11p MAC for VANETs where both safety messages and non-safety data are considered. Performance influencing parameters are taken into account. Mobility of vehicles is considered. The correlation among parameters and performance metrics are obtained through Markov chain model based analytical study. Probability of collision, probability of successful transmission, throughput, and delay expressions are acquired. Furthermore, the proposed performance model is validated with numerical results.

2.1.1 Performance Analysis

A vehicular ad hoc network (VANET) of N number of vehicles is considered. Vehicles are arbitrarily distributed and running through a multi-lane road. Calculating the vehicles number over a road segment follows a Poisson process. The probability mass function of N along an L_r length road segment can be given as

$$P(N=n)=\frac{(D_T L_r)^n e^{-D_T L_r}}{n!}, \quad n=0,1,....,N \tag{2.1}$$

where $D_T=\sum_{l=1}^{L} D_{T_l}, \qquad l\in\{1,2,........,L\}$.

D_T denotes the traffic density in L_T (number of vehicles/ distance/ lane) and D_{T_l} is vehicle density of lane l. Let r_t be the transmission range. The average number of vehicular nodes in r_t can be given as

$$N_{tr} = 2D_T r_t. \tag{2.2}$$

Let $\lambda_{vehicle}$ be the average arrival rate of vehicular nodes to transmission range r_t. $\lambda_{vehicle}$ and vehicle velocity v are linearly related and can be written as [46]:

$$\lambda_{vehicle} = n_L D_T v, \tag{2.3}$$

where n_L is the number of lanes in the road and v is the velocity which is uniformly distributed between v_{min} and v_{max}. The D_T changes linearly with the v as

$$D_T = J_T \left(1 - \frac{v}{v_f}\right), \tag{2.4}$$

where J_T is the traffic jam intensity at which traffic flow stops and v_f denotes the free-flow velocity. Therefore, the relationship among N, v, and r_t can be derived as

$$N = \frac{\lambda_{vehicle} r_t}{v}. \tag{2.5}$$

Average inter-vehicle distance β depends on the vehicle length and the legal gap which should be kept between vehicles, determined by the traffic department of the country.

$$\beta = D_{vehicle} + L_{vehicle} \tag{2.6}$$

where $D_{vehicle}$ is the legal distance between vehicles which should be kept and $L_{vehicle}$ is the vehicle length.

When a node has a safety message, the safety message is broadcast in the network through CCH. Nodes aiming to exchange non-safety data are called providers. A WAVE provider could be either a road-side unit or a vehicle. Providers initialize an IEEE 802.11p BSS. Providers advertise their presence and the offered services by periodically broadcasting WSA messages during the CCH interval. WSAs convey all the information identifying the provided WAVE services and the network parameters necessary to join the BSS, such as the unique identifier of the BSS (BSSID), the Provider Service IDentifier (PSID), the SCH frequency the BSS will use, timing information, the parameter sets to be used on the SCH, and the IP configuration parameters, etc. Nodes interested in the services offered by the provider, namely WAVE users, should monitor the CCH to learn about the existence and the operational parameters of available BSSs as advertised by WSAs; then they simply switch on the advertised SCH frequency during the SCH interval to join the detected and chosen BSS. Broadcast packets are never acknowledged, so failed transmissions of sm and WSAs, either due to collisions with other packets or channel impairments, cannot be detected. As a result, their contention window does not change.

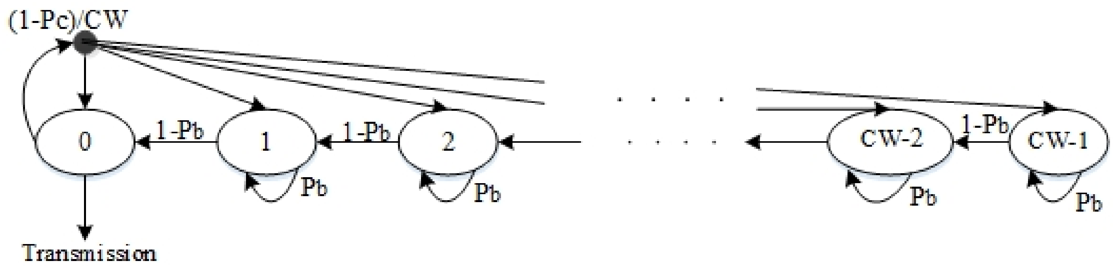

Figure 2.1 Markov chain model for backoff process

When a vehicle has a packet to transmit, starts to listen the channel. If the channel is sensed idle for DCF inter frame space (DIFS) time, the vehicle transmits. Otherwise, the vehicle initiates a random backoff before transmitting to reduce collision because there could be packet transmission by any of the remaining vehicles. Let $b(t)$ is the stochastic process which represent backoff time counter for a vehicular node at time t where b_c expresses the value of the backoff counter. Let CW denotes the contention window size, where $b_c \in (0, CW-1)$. The Markov chain for backoff method is illustrated in Fig. 1. The initial value of b_c is uniformly taken from [0, CW-1]. It is decreased by 1 when the channel is listened idle in a slot time, and paused in the present value when the channel becomes busy, and restarted when the channel becomes idle again for more than T_{DIFS}. The packet will be transmitted when b_c is 0. In addition, even if the channel is idle for DIFS period, a vehicle have to wait an arbitrary b_c between two sequential new packets transmissions to avoid channel capture. Let P_c and P_b be the probability of collision and channel busy, respectively.

Following transition probabilities can be given from Figure 2.1

$$P\{b_c | b_c + 1\} = 1 - P_b \quad b_c \in (0, CW-2), \tag{2.7}$$

$$P\{b_c | b_c\} = \frac{P_b}{CW} \quad b_c \in (0, CW-1), \tag{2.8}$$

$$P\{b_c | 0\} = \frac{1-P_c}{CW} \quad b_c \in (0, CW-1). \tag{2.9}$$

The b_c is decreased by 1 when the channel is listened idle in eq. (2.7), eq. (2.8) states that the b_c is paused at the present value when the channel becomes busy, and eq. (2.9) points that the packet will be sent immediately when the b_c is zero.

Let $b_{b_c} = \lim_{t \to \infty} P\{b(t) = b_c\}$, be the stationary distribution of the Markov chain. The following solution can be attained from Markov chain:

$$b_{b_c} = \frac{CW - b_c}{CW} b_0. \tag{2.10}$$

Since the sum of all possible states is one,

$$1 = \sum_{b_c=0}^{CW-1} b_{b_c} = \sum_{b_c=0}^{CW-1} \frac{CW - b_c}{CW} b_0. \tag{2.11}$$

So,

$$b_0 = \frac{2}{CW + 1}. \tag{2.12}$$

Let P_t be the probability of transmission that a vehicular node sends a packet in a slot time which can be defined as

$$P_t = b_0 = \frac{2}{CW + 1}. \tag{2.13}$$

The channel will be busy if minimum one vehicle is transmitting a packet within the r, then P_b can be written as

$$P_b = 1 - (1 - P_t)^N. \tag{2.14}$$

Collision occurs if minimum one of the existing $N - 1$ vehicles is transmitting a packet, then P_c can be written as

$$P_c = 1 - (1 - P_t)^{N-1}. \tag{2.15}$$

Let P_s be the probability of successful transmission that a transmitted packet is effectively received by the receiver which can be obtained as

$$P_s = \frac{NP_t(1 - P_t)^{N-1}}{P_b}. \tag{2.16}$$

Let $P_{parrival}$ be the possibility of packet arrival in each vehicle which follows a Poisson process. If λ is the mean arrival rate, then

$$P_{parrival}(n\ arrivals\ in\ interval\ T_e) = \frac{(\lambda T_e)^n e^{-\lambda T_e}}{n!}, \tag{2.17}$$

where T_e denotes expected period of a vehicular node in a Markov state. No packet arrival probability can be written as

$$P_{parrival}(0\ arrivals\ in\ interval\ T_e) = \frac{(\lambda T_e)^0 e^{-\lambda T_e}}{0!} = e^{-\lambda T_e}. \tag{2.18}$$

Therefore, $P_{parrival}$ can be given as

$$P_{parrival} = 1 - e^{-\lambda T_e}. \tag{2.19}$$

T_e can be given as

$$T_e = (1 - P_b)T_{slot} + P_b P_s T_s + P_b(1 - P_s)T_c \tag{2.20}$$

Here, T_{slot}, T_s, and T_c are the period of slot, successful, and collided transmission, respectively. Broadcast mode of safety messages (sm) and unicast mode of non-safety data (nsd) is considered. T_s, and T_c for sm and nsd can be written as

$$T_{s-sm} = \frac{L_h + L}{R_d} + T_{DIFS} + T_{delay}, \tag{2.21}$$

$$T_{s-nsd} = \frac{L_h + L}{R_d} + T_{SIFS} + T_{DIFS} + \frac{WSA}{R_c} + T_{delay}, \tag{2.22}$$

$$T_c = \frac{L_h + L}{R_d} + T_{DIFS} + T_{delay}, \tag{2.23}$$

where L_h denotes the MAC and PHY header lengths, L indicates the packet size, R_d and R_c express the system data and control packet transmission rate, respectively. T_{SIFS}, T_{DIFS}, and T_{delay} denotes the interval of short interframe space (SIFS), DIFS, and propagation delay, respectively.

Let S be the normalized system throughput, i.e. the data transmitted over the mean length of a slot time which can be defined as

$$S = \frac{E[data\ transmitted\ in\ a\ slot\ time]}{E[length\ of\ a\ slot\ time]} = \frac{E[p]}{T_e}, \tag{2.24}$$

where $E[.]$ represents the expectation operator. S for sm and nsd can be given as

$$S_{sm} = \frac{P_s P_b L}{(1 - P_b)T_{slot} + P_b P_s T_{s-sm} + P_b(1 - P_s)T_c}, \tag{2.25}$$

$$S_{nsd} = \frac{P_s P_b L}{(1 - P_b)T_{slot} + P_b P_s T_{s-nsd} + P_b(1 - P_s)T_c}. \tag{2.26}$$

Let $E[D]$ be the average delay of a successfully transmitted packet that is the mean time duration from the time when the packet is prepared to be transmitted in its MAC queue up to the time of successful transmission. In computing $E[D]$, the time interval of a packet which is dropped will not be counted. Therefore, $E[D]$ can be defined as

$$E[D] = E[T_{interval}] - E[P_{drop}]E[T_{drop}], \tag{2.27}$$

where $E[T_{interval}]$ denotes the average interval between two successful reception of packets at one receiver, $E[P_{drop}]$ is the mean number of dropped packets for a successful transmission, and $E[T_{drop}]$ is the mean duration to drop a packet. $E[T_{interval}]$ can be derived from throughput for sm and nsd as

$$E[T_{interval-sm}] = \frac{NE[p]}{S} = NT_{e-sm}, \tag{2.28}$$

$$E[T_{interval-nsd}] = \frac{NE[p]}{S} = NT_{e-nsd}. \tag{2.29}$$

If P_{fdrop} is the probability that a packet is dropped lastly, then $E[P_{drop}]$ can be written as

$$E[P_{drop}] = \frac{P_{fdrop}}{1 - P_{fdrop}}. \tag{2.30}$$

$E[T_{drop}]$ can also be expressed as

$$E[T_{drop-sm}] = E[X_{drop}]T_{e-sm}, \tag{2.31}$$

$$E[T_{drop-nsd}] = E[X_{drop}]T_{e-nsd}, \tag{2.32}$$

where $E[X_{drop}]$ denotes the mean number of slot times for a dropped packet which can be given as

$$E[X_{drop}] = \frac{CW + 1}{2}. \tag{2.33}$$

Thus, the $E[D]$ can be expressed by using equation from (2.28) to (2.33) as

$$E[D_{sm}] = T_{e-sm}\left(N - \frac{P_{fdrop}}{1 - P_{fdrop}} \times \frac{CW + 1}{2}\right). \tag{2.34}$$

$$E[D_{nsd}] = T_{e-nsd}\left(N - \frac{P_{fdrop}}{1 - P_{fdrop}} \times \frac{CW + 1}{2}\right). \tag{2.35}$$

2.1.2 Numerical Results

This section assesses the performance of IEEE 802.11p MAC for VANETs for sm and nsd as well as ascertains the analytical study. The numerical analysis is performed in the MATLAB. Two lane road with 5 m width each is considered. Table 2.1 presents the value of parameters utilized in the numerical analysis.

Table 2.1 Value of parameters used in numerical analysis

Parameter	**Value**
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ μs	20, 10, 50 ,1
L_h, L, WSA (bytes)	50, 512, 24
R_c, R_d (Mbps)	1, 11
Contention Window size, CW	64
Number of vehicles, N	0-100
Transmission range, r_t (m)	500
Density of vehicles, D_T (veh/m)	0.01
Vehicle velocity, v (km/h)	100

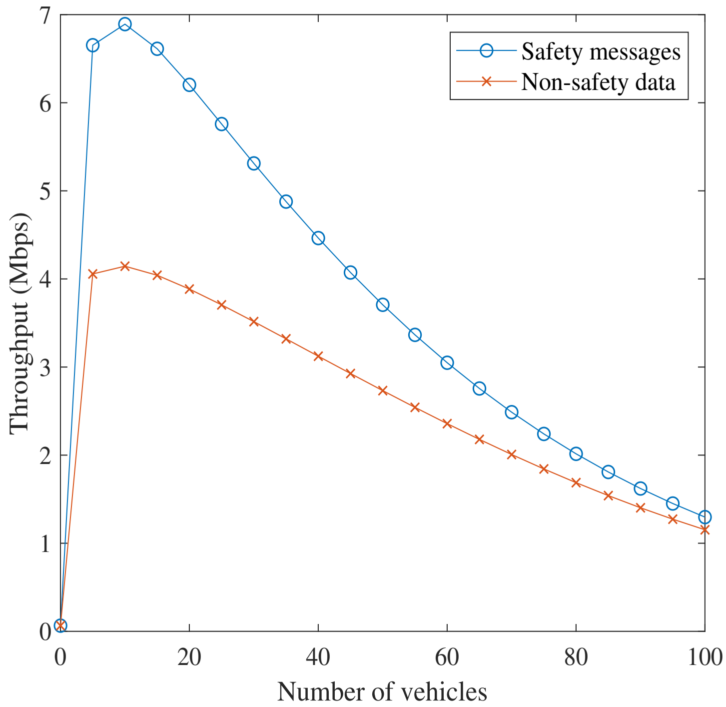

Figure 2.2 Throughput against number of vehicles

Figures 2.2 and 2.3 demonstrate throughput against number of vehicles and vehicle density, respectively. Since fewer number of vehicles may not cause collision, throughput starts to increase with increasing vehicles, but after the number of vehicles more increases, then additional vehicles would cause more collisions and throughput falls. In both figures, it is noticeable that throughput goes to a highest point, then it starts to fall which may slightly differs for sm and nsd. Therefore, there is a certain number of vehicles or vehicle density that could provide maximum throughput. To have optimum throughput, a parameter can be optimized based on number of vehicles

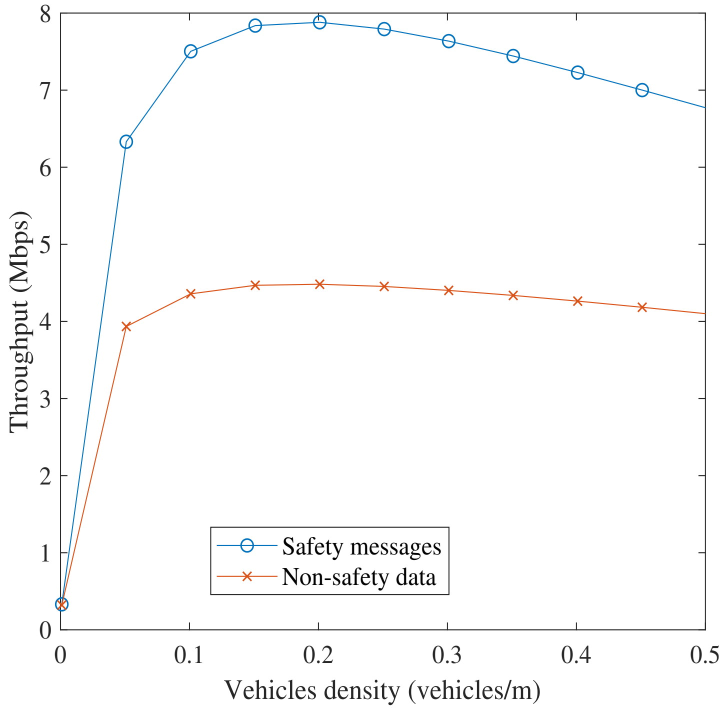

Figure 2.3 Throughput versus vehicle density

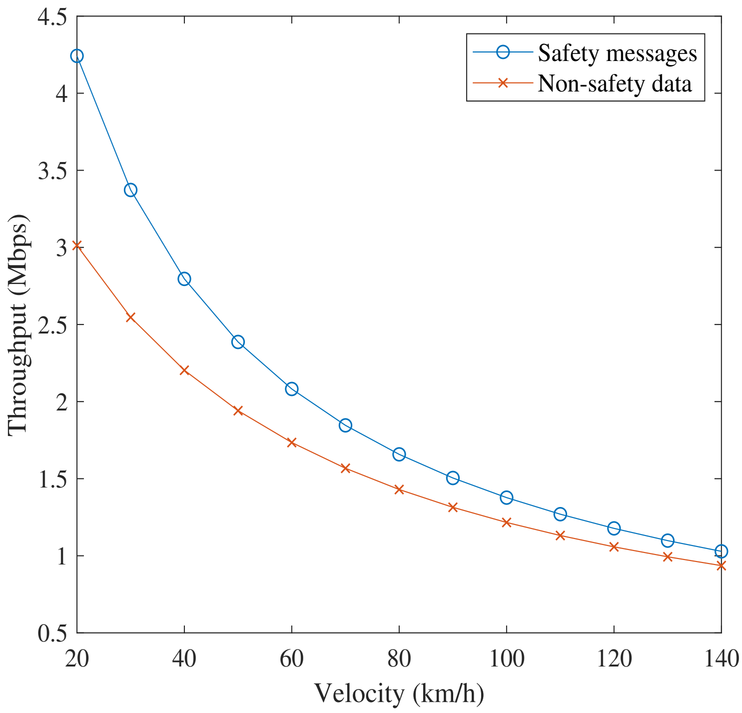

Figure 2.4 Throughput versus velocity

or vehicle density in the network. From eq. (2.25) and (2.26), throughput is achieved from which it is understandable that throughput depends on transmission probability. From eq. (2.13), it is obvious that transmission probability depends on CW size.

Therefore, CW size can be optimized which will adopt the optimum transmission probability that will maximize throughput.

Figure 2.4 exhibits the throughput against vehicle velocity. Since high vehicle mobility can results in rapid topology changes with frequent link breakage which causes unstable communications due to collision and packet loss, the throughput is decreasing with the increment of vehicle velocity. In Figures 2.2, 2.3, and 2.4, it can be seen that sm have higher throughput than nsd because sm are broadcast without any other control message broadcast and nsd is transmitted after WSA broadcast.

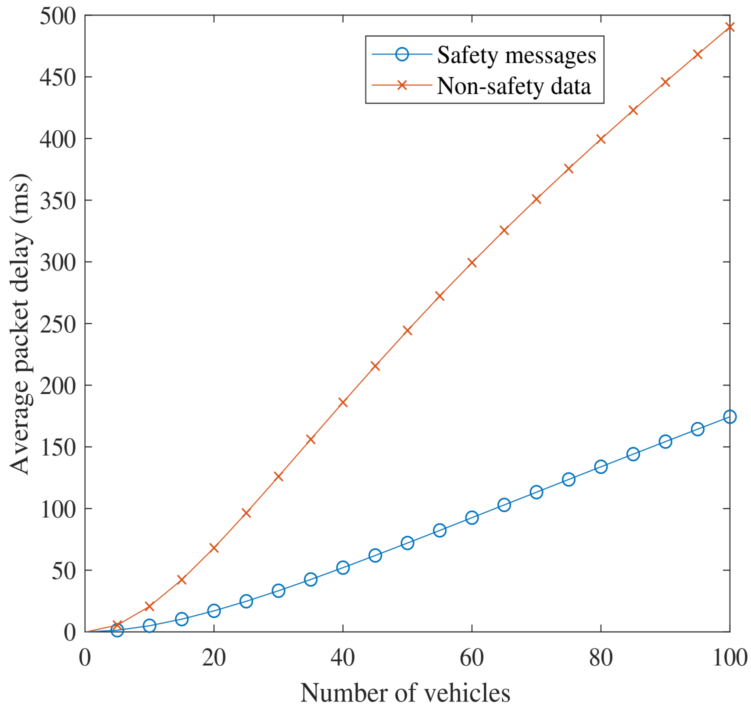

Figure 2.5 Average delay against number of vehicles

Figures 2.5 and 2.6 present the average packet delay against number of vehicles and velocity, respectively. Since increment of the number of vehicles would raise the number of packets to be delivered, more packets will contend for transmission that will keep channel busy more and the probability of collision will be increased. Therefore, the average delay is growing with the rise of vehicles number. Average delay is also increasing with the velocity of vehicles because high mobility changes network topology rapidly which causes delay in packet delivery. It is also observable that the average delay of sm is lower than nsd. Since no other control packets are broadcast before sm, sm are broadcast immediately after getting the channel. On the other hand, nsd is transmitted after broadcast of WSA. Therefore, there is an extra broadcast of WSA and there is contention for this broadcast which increases the

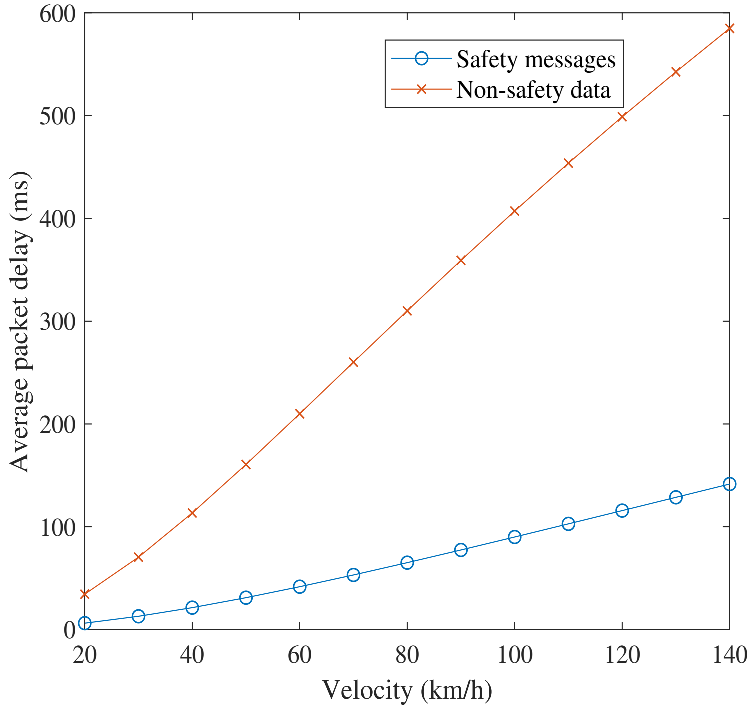

Figure 2.6 Average delay against velocity

average delay for nsd. Though the delay of safety messages is lower than non-safety data, when there is high traffic, the IEEE 802.11p MAC can not fulfill the strict delay requirement of 100 ms for safety messages.

2.2 Enhanced Distributed Channel Access Function

DCF does not differentiate among different types of traffics. On the other side, EDCAF supports QoS at the MAC layer. According to EDCAF, there are four access categories (ACs) which are denoted as AC0, AC1, AC2, and AC3. The acronym of AC0, AC1, AC2, and AC3 are VO, VI, BE, and BK, respectively. AC0 denotes voice, AC1 expresses video, AC2 represents best effort, and AC3 indicates back ground. Different EDCA parameters for instance minimum contention window (CW_{min}), maximum contention window (CW_{max}), and arbitration interframe space number (AIFSN) etc. define the priority among ACs. To compete for transmission opportunities (TXOPs), each AC queue acts as a distinct DCF station with its own parameters. EDCA parameter for each AC is given in Table 2.2. The prioritization process within each STA is presented in Figure 2.7.

For different ACs, there are four transmission queues and four distinct EDCAF. Since the EDCA parameter is not same for each AC, each AC queue employs distinct AIFS, CW_{min}, and CW_{max}. To implement priority of the transmission, EDCAF uses arbitration

Table 2.2 EDCA parameters for individual AC

AC	Acroyn	Traffic Type	EDCA parameter		
			CW_{min}	CW_{max}	AIFSN
AC3	BK	Background	qCW_{min}	qCW_{max}	9
AC2	BE	Best effort	qCW_{min}	qCW_{ax}	6
AC1	VI	Video	(qCW_{min}+1)/2-1	CW_{min}	3
AC0	VO	Voice	(qCW_{min}+1)/4-1	(qCW_{min}+1)/2-1	2

inter-frame space (AIFS) which is a new inter frame space (IFS). T_{AIFS} is the idle interval after a busy interval which can be obtained from the AIFSN value of the AC which can be given as

$$T_{AIFS}[AC] = AIFSN[AC] \times T_{slot} + T_{SIFS}. \tag{2.36}$$

In EDCAF, when a packet reaches at an AC queue in a vehicle, the packet will be sent if the channel is listened idle and retains idle for T_{AIFS}. Else, since the channel is busy, vehicle will carry on to listen the channel until the channel turns into idle and retains idle for T_{AIFS}. The vehicle will start a backoff process to reduce collision probability with packets being transmitted by other vehicles. Besides, even a vehicle get the channel idle for T_{AIFS}, the vehicle have to wait an arbitrary backoff time between two sequential new packets delivery to escape channel capture. At first, the vehicle initiates a b_c with a beginning value arbitrarily taken between 0 and CW_{min}. b_c will be decreased by 1 when channel is idle, paused in the current value if sensed busy,

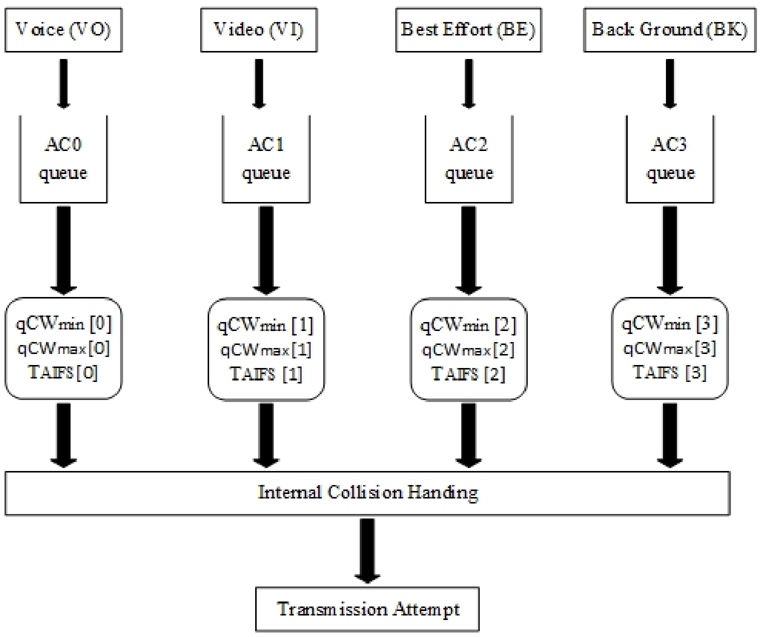

Figure 2.7 Outline of EDCA mechanism

resumed if the channel turns into idle once more and stays idle for T_{AIFS}. When the b_c is zero, the packet will be transmitted. A vehicle can send data only at the start of each slot time. An internal collision will happen when more than one AC queue in a vehicle has packets to send at the identical time. If an internal collision arises, the vehicle will allow the transmission to the highest priority AC queue. Meanwhile, other lower priorities AC queues will initiate to backoff and later the packet will be delivered.

2.2.1 Performance Analysis

Using (2.13) and (2.15), P_c can be written as

$$P_c = 1 - \left(\frac{CW[AC] - 1}{CW[AC] + 1}\right)^{N-1}. \tag{2.37}$$

Using (2.13) and (2.14), P_{busy} can be written as

$$P_b = 1 - \left(\frac{CW[AC] - 1}{CW[AC] + 1}\right)^{N}. \tag{2.38}$$

Using (2.13) and (2.16), P_s can be written as

$$P_s = \frac{2N}{\frac{(CW[AC]+1)^N}{(CW[AC]-1)^{N-1}} - CW[AC] + 1}. \tag{2.39}$$

Te can be obtained from Eq. (2.20). Due to broadcast nature, T_s and T_c are equal which can be given as

$$T_s = T_c = \frac{L_h + L}{R_d} + T_{SIFS} + T_{AIFS}[AC] + T_{delay}. \tag{2.40}$$

Therefore, throughput S can be obtained from eq. (2.24) as follows:

$$S = \frac{E[p]}{T_e} = \frac{P_s P_b L}{(1 - P_b)\, T_{slot} + P_b P_s T_s + P_b(1 - P_s) T_c}. \tag{2.41}$$

By using Eq. (2.37) - Eq. (2.41), the normalized throughput can be derived as from which

$$S = \frac{\frac{2N(CW[AC]-1)^{N-1}}{(CW[AC]+1)^N} L}{\left(\frac{CW[AC]-1}{CW[AC]+1}\right)^N T_{slot} + \frac{2N(CW[AC]-1)^{N-1}}{(CW[AC]+1)^N} T_S + \frac{(CW[AC]+1)^N - (CW[AC]-1)^N - 2N(CW[AC]-1)^{N-1}}{(CW[AC]+1)^N} T_c} \tag{2.42}$$

$E[D_{access}]$ is the mean access delay that is the mean time duration for a packet transmission from contending for the channel to the successful transmission of the packet or drop of the packet. Here two events may happen:

1. The packet transmission can be successful with a collision and without a collision, or

2. The packet can be dropped because of collision.

Therefore, $E[D_{access}]$ can be defined as

$$E[D_{access}] = E\left[T_{waiting}\right]P_c(1-P_c) + E\left[T_{waiting}\right]P_c, \tag{2.43}$$

where $E[T_{waiting}]$ denotes the mean waiting time of an AC queue at backoff which can be given as

$$E\left[T_{waiting}\right] = \frac{CW[AC]-1}{2}T_e. \tag{2.44}$$

$E[T_{interval}]$ is the mean packet interval time at one receiver between two successful reception of packets which can be achieved from throughput as

$$E[T_{interval}] = \frac{NE[p]}{S} = N.T_e \tag{2.45}$$

$E[T_{drop}]$ is the mean time to drop a packet which can be given as:

$$E\left[T_{drop}\right] = E\left[X_{drop}\right].T_e \tag{2.46}$$

where $E[X_{drop}]$ is the mean number of slot times for a dropped packet which can be written as

$$E\left[X_{drop}\right] = \frac{CW[AC]+1}{2} \tag{2.47}$$

$E[P_{drop}]$ can be obtained from eq. (2.30). Using Eq. (2.45) - Eq. (2.47) in eq. (2.27) the average packet delay $E[D]$ can be given as

$$E[D] = T_e(N - \frac{P_{fdrop}}{1-P_{fdrop}}.\frac{CW[AC]+1}{2}) \tag{2.48}$$

2.2.2 Numerical Results

The impact of IEEE 802.11p EDCAF is evaluated and analytical analysis is verified. The numerical analysis is accomplished in MATLAB. A VANET of 20 vehicles is considered where vehicles are distributed arbitrarily. Table 2.3 presents the parameters value used in numerical results.

Figure 2.8 exhibit throughput against the number of vehicles. All ACs are shown. Throughput of each AC queue starts to increase with the number of vehicles, then

Table 2.3 Value of parameter used in numerical results

Parameter	Value	Parameter	Value
$CW_{min}[0]$	3	$CW_{min}[2]$	7
$CW_{max}[0]$	7	$CW_{max}[2]$	1023
$CW_{min}[1]$	3	$CW_{min}[3]$	15
$CW_{max}[1]$	15	$CW_{max}[3]$	1023
$AIFSN[0]$	2	$AIFSN[2]$	6
$AIFSN[1]$	3	$AIFSN[3]$	9
T_{slot}, T_{delay} μs	20, 1	T_{SIFS} μs	10
L_h, L (bytes)	50, 1024	R_d, R_c, λ (Mbps)	11, 1, 0.5

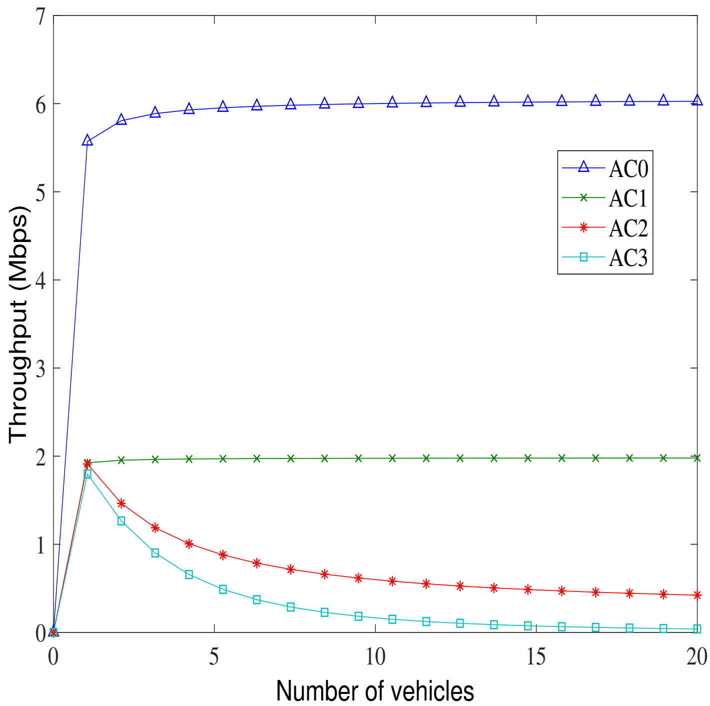

Figure 2.8 Throughput versus number of vehicles

initiates to fall after a certain point which is also seen in Figures 2.9 that shows transmission probability against the number of vehicular nodes. With increase of the number of vehicular nodes, transmission probability as well as throughput are increasing until a certain point because packets transmission from that number of vehicular nodes would not originate many collisions. When further more packets arrive and contend for transmission with further increased number of vehicles, more collisions occur that results in fall of throughput and transmission probability. Therefore, to maximize the transmission probability as well as throughput for each AC queue, there is a certain number of vehicular nodes.

Figure 2.10 presents normalized throughput of ACs versus packet arrival probability.

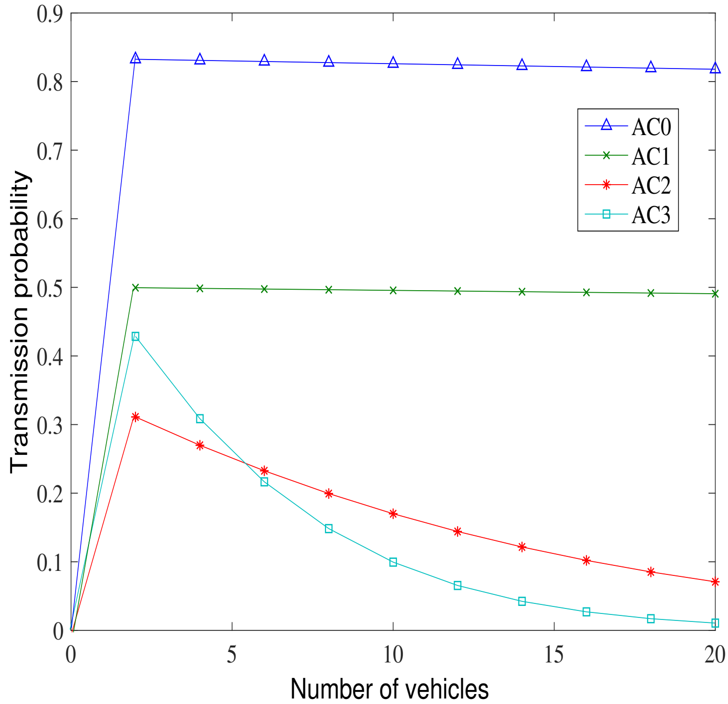

Figure 2.9 Transmission probability against number of vehicles

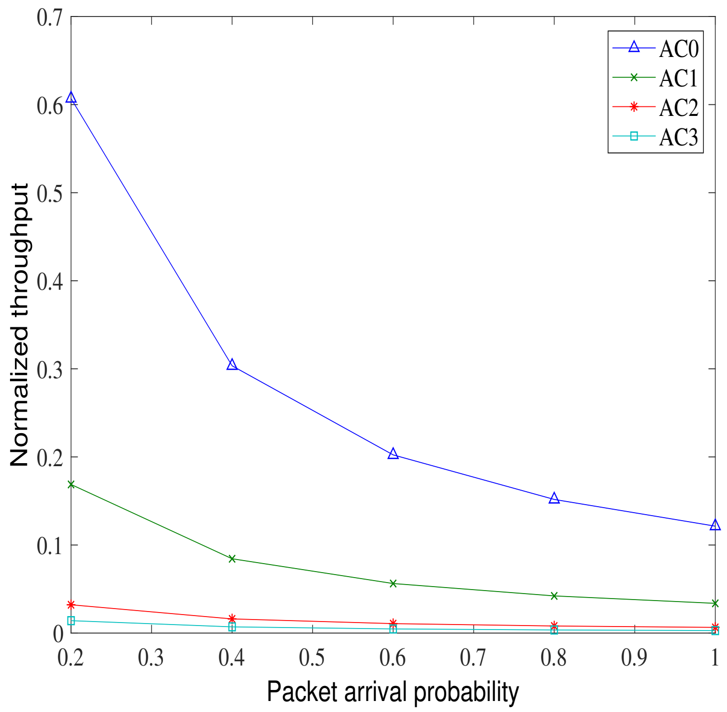

Figure 2.10 Normalized throughput against packet arrival probability

Normalized throughput decreases with increase of packet arrival probability. Since with increase of packet arrival probability in AC queue, more packets will compete for packet delivery in the identical time slot that resuls in more collision which degrades normalized throughput.

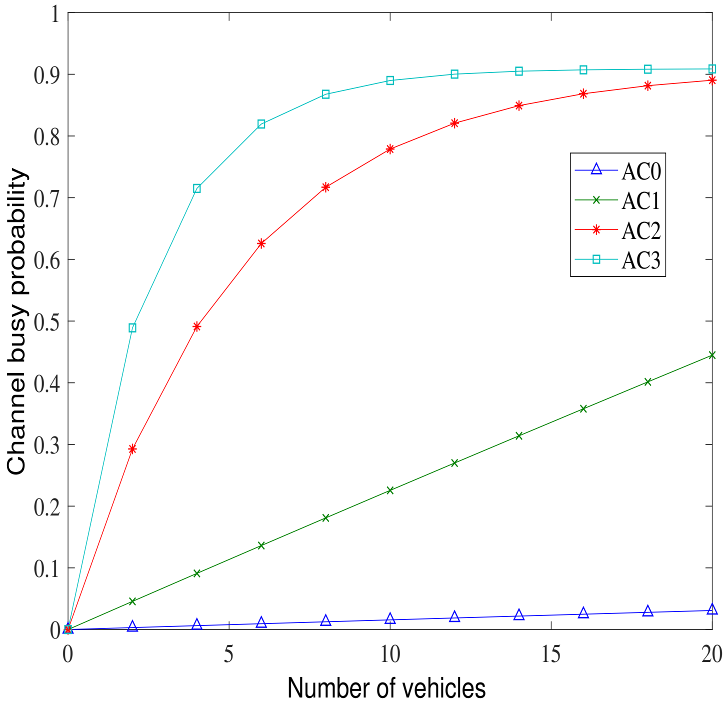

Figure 2.11 Channel busy probability against number of vehicles

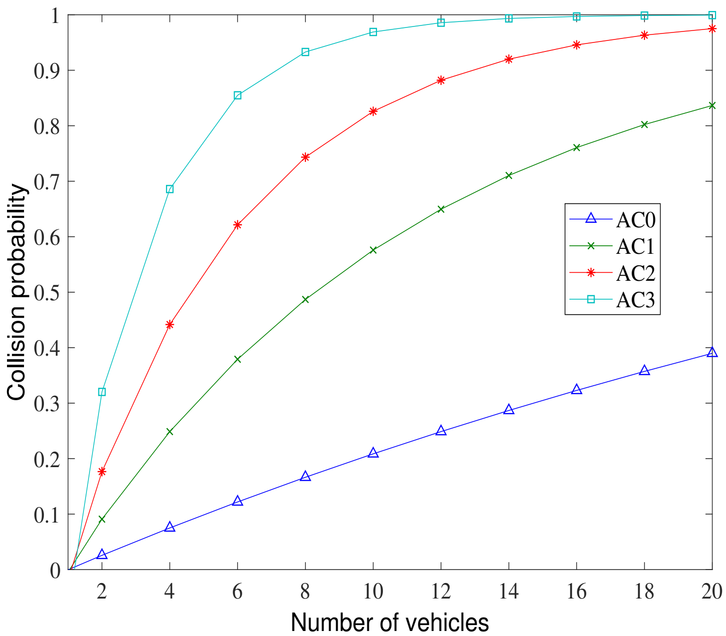

Figure 2.12 Collision probability against number of vehicles

Figures 2.11 and Figures 2.12 illustrate channel busy probability as well as collision probability against number of vehicles, respectively. All ACs are shown. When the number of vehicles goes up, the probability of channel busy as well as collision increases. Since with increase of vehicular nodes more packets will compete for transmission in AC queue, the channel will be busier and more packets would cause more collisions.

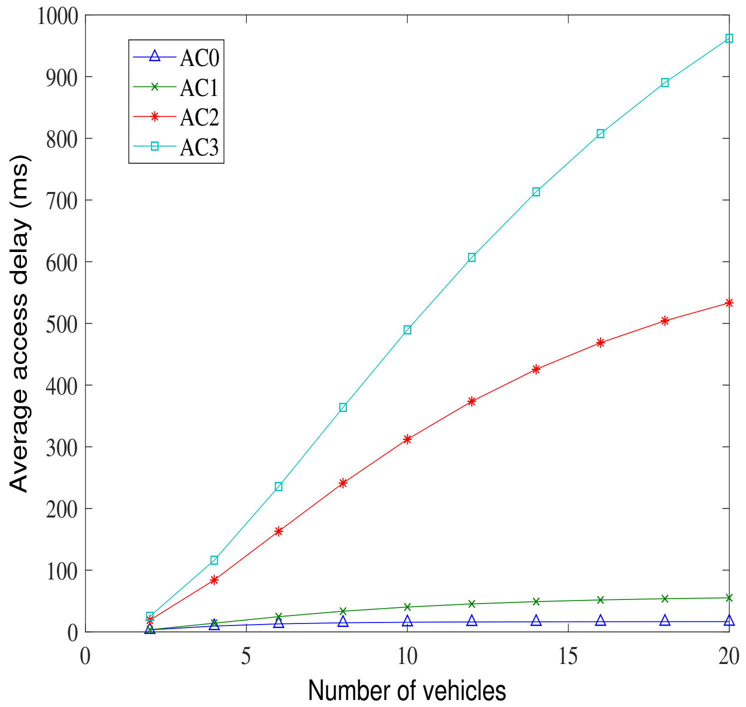

Figure 2.13 Average access delay against number of vehicles

Figures 2.13 and 2.14 demonstrate the average access delay as well as average packet delay of each AC queue against the number of vehicles. For every AC queue, average access delay as well as average packet delay upturn with the number of vehicles. When there will be additional packets from more number of vehicles, the contention time will be increased because the channel will be busy and counter of backoff will be paused in the present value. The more channel will be busy, the more backoff counter will be paused that results in higher delay. Collision probability will also increase with increase of the number of vehicular nodes due to more packets transmission attempts in the identical time slot which also causes increment of delay because after collision backoff stage goes to next stage and backoff counter becomes double. Delay will increase with the increase of backoff.

From Figure 2.8 to Figure 2.14, it is comprehended that throughput of AC0 is higher than AC1, AC1 is higher than AC2, and AC2 is higher than AC3, and in the case of delay AC0 is lower than AC1, AC1 is lower than AC2, and AC2 is lower than AC3. The ACO has highest throughput but lowest delay and AC3 has lowest

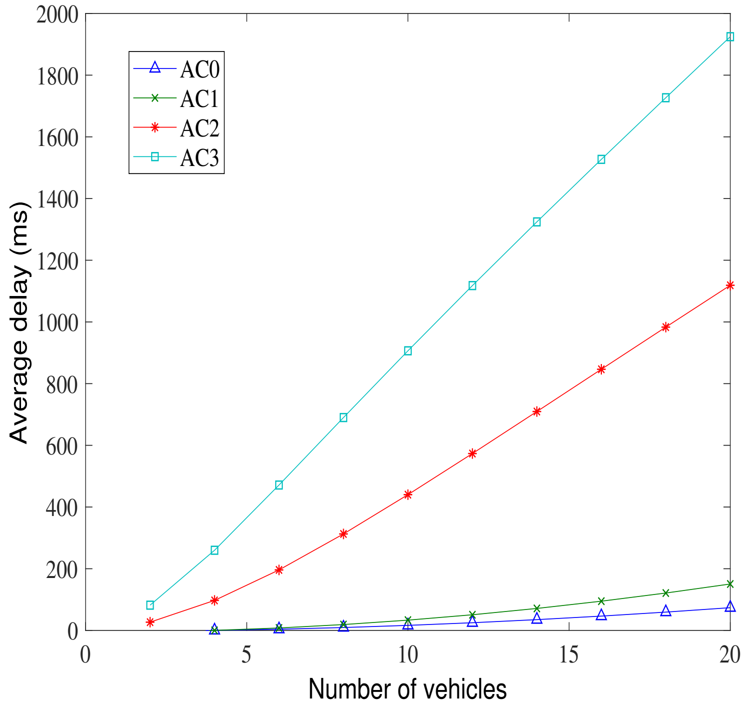

Figure 2.14 Average delay against number of vehicles

throughput but highest delay. For throughput, AC0>AC1>AC2>AC3 and for delay, AC0<AC1<AC2<AC3. The backoff process makes it possible. Since T_{AIFS} is different due to different AIFSN value, packets of different ACs have different T_{AIFS}, different ACs have different backoff. AIFSN value of ACO is lowest and AC3 is highest. For AIFSN value, AC0<AC1<AC2<AC3. Not only AIFSN value but also CW_{min} and CW_{max} influence backoff process. The lowest CW_{min} and CW_{max} has AC0 and highest CW_{min} and CW_{max} has AC3. Therefore, due to T_{AIFS}, CW_{min} and CW_{max}, packets in AC0 is transmitted first, then AC1, then AC2, then AC3 which results in highest throughput in AC0 and lowest delay in AC0, and so on.

2.3 Channel Fading and Capture Effect

Two major factors which influence the performance of VANETs in practical transmission are bit error and channel capture. Earlier studies scrutinized these effects separately. In this section, a comprehensive analysis is presented that integrates the two essential factors. To assess the performance of IEEE 802.11p MAC for VANETs under channel fading and capture effect, an analytical model based on Markov chain model is presented. The parameters that could impact performance are studied. The relationship among parameters and performance metrics are derived. All faded channels such as Nakagami, Rayleigh, and Rician faded channels are considered.

The probability of successful and unsuccessful transmission, probability of frame capture, outage probability, Bit error rate (BER), throughput, and delay expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented.

2.3.1 Performance Analysis

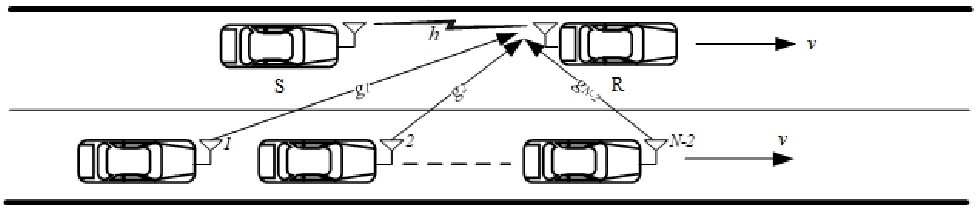

Figure 2.15 System model

System model is presented in Figure 2.15. A packet is subject to interference from simultaneous transmission (collision) as well as background noise. The signal to interference-plus-noise ratio (SINR) at the receiver can be given as

$$\gamma_R = \frac{\sigma_R |h|^2}{\sigma_{Noise} + \sum_{i=1}^{k} \sigma_R^{(i)} |g_i|^2}, \quad k \in [1, N-2], \tag{2.49}$$

where σ_R denotes power of the transmission at the receiver, $\sigma_R^{(i)}$ is power of background noise, σ_{Noise} indicates power of i-th interfering transmissions at receiver and h is channel fading coefficient between transmitter (S) and the receiver (R), g_i is channel fading coefficient at the i-th interferer. Sum becomes null when there is no collision, i.e. $k = 0$. After some simplification in (13), SINR can be given by

$$\gamma_R = \frac{Y}{Z} \tag{2.50}$$

where $Y = \sigma_R |h|^2 / \sigma_{Noise}$ and $Z = \sum_{i=1}^{k} \sigma_R^{(i)} |g_i|^2 / \sigma_{Noise} + 1$. Assuming power-controlled nodes in infrastructure mode, if there are i interfering frames, capture probability can be given as [70]

$$P_{cc}(z_o g(S_f)|i) = P(\gamma_R > z_o g(S_f)|i) = 1 - F_{\gamma_R}(z_o), \tag{2.51}$$

where z_o and $g(Sf)$ are capture ratio and processing gain of correlation receiver, respectively. $F_{\gamma_R}(.)$ denotes cumulative distribution function (CDF) of SINR at receiver. In the case of direct sequence spread spectrum (DSSS), utilizing an 11-chip spreading factor ($S_f = 11$), $g(Sf)$ can be given as

$$g(S_f) = \frac{2}{3S_f}. \tag{2.52}$$

P_{R_i} is probability of i interfering frames initiated from N competing nodes in a time slot which can be given as

$$P_{R_i} = \begin{pmatrix} N \\ i+1 \end{pmatrix} P_t^{i+1}(1-P_t)^{N-i-1}. \tag{2.53}$$

P_{cap} is frame capture probability which can be written as

$$P_{cap} = \sum_{i=1}^{N-1} P_{R_i} P_{cc}(z_o g(S_f)|i). \tag{2.54}$$

P_s is successful transmission probability that a transmitted packet is delivered to R which can be given as

$$P_s = \frac{NP_t(1-P_t)^{N-1} + P_{cap}}{P_b}. \tag{2.55}$$

P_{us} is unsuccessful transmission probability. A packet delivery can be unsuccessful because of collision at MAC layer and/or an errored frame because of channel fading and/or noise at physical layer. Let P_{ef} be errored frame probability. P_{us} can be given as

$$\begin{aligned} P_{us} &= 1-(1-P_c)(1-P_{ef}) \\ &= 1-(1-P_t)^{N-1}(1-P_{ef}). \end{aligned} \tag{2.56}$$

Let T_e be the expected time of a node in a Markov state which can be written as

$$T_e = (1-P_b)T_{slot} + P_b P_s (1-P_{ef})T_s + P_b(1-P_s)T_c + P_b P_s P_{ef} T_{ef}, \tag{2.57}$$

where T_{slot}, T_c, T_s, and T_{ef} are period of a slot, collided, successful, and errored frame transmission, respectively. sm is of broadcast mode and nsd is of unicast mode. For sm and nsd, T_s, T_c, and T_{ef} can be given as

$$T_{s-sm} = 3T_{SIFS} + T_{DIFS} + (N-1)T_{RTS} + (N-1)T_{CTS} + \tfrac{(N-1)L}{R_d} + (N-1)T_{ACK} + T_{delay}, \tag{2.58}$$

$$T_{s-nsd} = 3T_{SIFS} + T_{DIFS} + T_{RTS} + T_{CTS} + \tfrac{L}{R_d} + T_{ACK} + T_{delay}, \tag{2.59}$$

$$T_c = T_{DIFS} + T_{SIFS} + T_{RTS} + T_{delay}, \tag{2.60}$$

$$T_{ef} = 2T_{SIFS} + T_{DIFS} + T_{RTS} + T_{CTS} + \frac{L}{R_d} + T_{delay} \tag{2.61}$$

where T_{DIFS}, T_{SIFS}, T_{CTS}, T_{RTS}, T_{ACK}, and T_{delay} are duration of DIFS, short inter frame space (SIFS), CTS, RTS, acknowledgment (ACK), and propagation delay, respectively. R_d and L are transmission rate and packet size, respectively. The average γ_R of the received signal at d distance with path loss is [71]

$$\bar{\gamma}_R = \frac{G_r G_t \lambda^2 \sigma_R}{\sigma_{Noise}(4\pi)^2 d^{\alpha}}, \tag{2.62}$$

where $G_r = G_t = 4\pi/\lambda^2$ are antenna gain for the R and S and $\lambda = c/f$ is signal wavelength. α represents path loss exponent.

To include the impact of fading, a block fading pattern is taken into consideration in which a packet to be sent is split into B blocks (or periods of coherence). B value depends on the speed of the vehicle. When speed is increased and coherence time is reduced, B is large. B also depends on packet size which can be given as

$$B = \frac{L}{T_{coh}\log(1+\gamma_{th})}, \tag{2.63}$$

where γ_{th} is threshold value of SINR and T_{coh} is coherence time

$$T_{coh} = \sqrt{\frac{9}{16\pi f_{dop}}}, \tag{2.64}$$

where f_{dop} denotes doppler shift that is

$$f_{dop} = \frac{v}{c} f \cos(\theta). \tag{2.65}$$

Here, c denotes speed of light in the direction of movement towards the transmitter, v is vehicle velocity, and f indicates carrier frequency. θ represents the angle between received signal and direction of vehicle.

2.3.1.1 Nakagami-m Fading Channel

Nakagami-m fading model is a more general distribution than the Rayleigh and Rician fading models, and is a channel model that characterizes rapid fading over long distances.

Since $|h|$ and $|g_i|$ Nakagami-m distribution, probability density function (PDF) as well as cumulative distribution function (CDF) of Y can be given as

$$f_Y(y) = \frac{1}{y\Gamma(m)} e^{\left(-\frac{my}{\overline{Y}}\right)} \left(\frac{my}{\overline{Y}}\right)^m, \tag{2.66}$$

$$F_Y(y) = \frac{1}{\Gamma(m)} \Gamma(m, 0, \frac{my}{\overline{Y}}), \tag{2.67}$$

where m denotes shape parameter of distribution and $\Gamma(.)$ indicates Gamma function. $\Gamma(.,.,.)$ is generalized regularized incomplete Gamma function. $\overline{Y} = \sigma_R \Omega / \sigma_{Noise}$ and $\Omega = E[h^2]$. $E[.]$ denotes expectation operator. For PDF of Z, Nakagami-m variables is derived as [72]

$$f_Z(z) = \frac{\vartheta_I^{\vartheta_I} (z-1)^{\vartheta_I - 1}}{\Gamma(\vartheta_I)} e^{\left(-\frac{\vartheta_I (z-1)}{\bar{Z}}\right)}, \tag{2.68}$$

where $\bar{Z} = P_I \Omega_I / \sigma_{Noise}, \Omega_I = E[\sum_{i=1}^{k} |g_i|^2]$ and $\vartheta_I = \Omega_I^2 / E\left[\left(\sum_{i=1}^{k} |g_i|^2\right)^2\right] - \Omega_I^2$. The CDF of γ_R can be calculated as

$$\begin{gathered} F_{\gamma_R}(\gamma) = \int_0^{\infty} F_Y(z\gamma) f_Z(z) dz \\ = \frac{\vartheta_I^{\vartheta_I} e^{\left(-\frac{\vartheta_I}{\bar{Z}}\right)}}{\Gamma(\vartheta_I)\Gamma(m)\bar{Z}^{\vartheta_I}} \int_0^{\infty} (z-1)^{\vartheta_I - 1} e^{\left(-\frac{Z\vartheta_I}{\bar{Z}}\right)} \Gamma(m, 0, \frac{mz\gamma}{\overline{Y}}) dz \\ = \frac{\vartheta_I^{\vartheta_I} e^{\left(-\frac{\vartheta_I}{\bar{Z}}\right)}}{\Gamma(\vartheta_I)\Gamma(m)\bar{Z}^{\vartheta_I}} \sum_{n=0}^{\vartheta_I - 1} C_{\vartheta_{I-1}}^{n} (-1)^n \\ \times \sum_{r=0}^{\infty} \left(-\frac{\vartheta_I}{\bar{Z}}\right)^r \frac{1}{r!} G_{2,3}^{2,1} \left(\frac{\gamma m}{\overline{Y}} \Big|_{n-r-\vartheta_I, m, 0}^{1, n+1-r-\vartheta_I}\right), \end{gathered} \tag{2.69}$$

where $G_{.,.}^{.,.}(.)$ symbolizes Meijer-G function and $C_{\vartheta_I - 1}^{n} = (\vartheta_I - 1)!/(\vartheta_I - 1 - n)!n!$ is binomial coefficient. When the Nakagami-m fading parameter is too large ($m \to \infty$), it converges to the AWGN channel. When $m = 1$, it gives the Rayleigh distribution.

The outage probability P_{outage} is the probability when SINR of received signal γ_R is less than SINR threshold γ_{th} which can be given as

$$P_{outage} = P(\gamma_R < \gamma_{th}) = \int_0^{\gamma_{th}} f_{\gamma_R}(x) dx = F_{\gamma_R}(\gamma_{th}). \tag{2.70}$$

Since packet is divided into B blocks, P_{ef} can be written as,

$$P_{ef} = 1 - (1 - P_{outage})^B. \tag{2.71}$$

2.3.1.2 Rayleigh Fading Channel

In cases where there is no line of sight between the receiver and the transmitter, communication takes place entirely from the surrounding buildings with signals reaching the receiver because of reflection, refraction and scattering. If the components of the transmitted signals are zero-averaged and random variable with the same variance, the envelope of this signal is distributed as Rayleigh distribution which is one of the channel type that has the worst effect on error performance of the system. When $m = 1$ in (2.69), the CDF of SINR under Rayleigh fading channel at the receiver can be obtained.

The P_{outage} of proposed system over Rayleigh fading channel is also can be achieved from (2.70) after using $m = 1$.

The packet errored frame probability P_{ef} can be derived as

$$\begin{aligned} P_{ef} &= 1-(1-P_{outage})^{B} \\ &= 1-\left[1-\frac{\vartheta_I^{\vartheta_I} e^{\left(-\frac{\vartheta_I}{\bar{Z}}\right)}}{\Gamma(\vartheta_I)\bar{Z}^{\vartheta_I}} \sum_{n=0}^{\vartheta_I-1} C^{n}_{\vartheta_{I-1}} (-1)^n \right. \\ &\quad \left. \times \sum_{r=0}^{\infty} \left(-\frac{\vartheta_I}{\bar{Z}}\right)^{r} \frac{1}{r!} G^{2,1}_{2,3}\left(\frac{\gamma_{th}}{\overline{Y}}\Big|^{1,n+1-r-\vartheta_I}_{n-r-\vartheta_I,1,0}\right)\right]^{B}. \end{aligned} \tag{2.72}$$

2.3.1.3 Rician Fading Channel

In the case of a line of sight between S and R in the wireless communication system, or if there is a more dominant transmission path compared to other transmission paths, the fading coefficients appear to be Rician distribution. While the variances of Gaussian processes that provide the formation of this channel model are the same, their mean can be different from zero. Here, it is the non-zero means of Gaussian processes that determine the average power of the direct transmission path or the dominant transmission path. The PDF and CDF of for Rician fading channel model is expressed as [73],

$$f_Y(y) = \frac{2y(K+1)}{\overline{Y}} e^{\left(-K-\frac{(K+1)y}{\overline{Y}}\right)} \times I_0\left(2\sqrt{\frac{K(K+1)y}{\overline{Y}}}\right), \tag{2.73}$$

$$F_Y(y) = 1-Q_1\left(\sqrt{2K}, \sqrt{\frac{y2(K+1)}{\overline{Y}}}\right), \tag{2.74}$$

where K is power in line of sight path over power in scattered multipath components. Rician distribution converges to AWGN channel in case of and Rayleigh channel in case of $K = 0$. $I_0(.)$ denotes zero order Bessel function. $Q_1(.,.)$ is Marcum-Q function.

For PDF of Z, it can be given as [73]

$$f_Z(z) = \frac{2(z-1)(\vartheta_I+1)}{\bar{Z}^2} e^{\left(-\vartheta_I - \frac{(\vartheta_I+1)(z-1)}{\bar{Z}}\right)} \times I_0\left(2\sqrt{\frac{K(K+1)(z-1)}{\bar{Z}}}\right). \tag{2.75}$$

For Rician fading channel, the CDF of γ_R can be calculated as

$$\begin{aligned} F_{\gamma_R}(\gamma) = \int_0^\infty F_Y(z\gamma) f_{\gamma_Z}(z) dz = \frac{2(\vartheta_I+1)e^{-K}}{\bar{Z}^2} \\ \times \int_0^\infty (z-1)\left(\sum_{\zeta=0}^\infty (K)^\zeta \Gamma\left(1+\zeta, \frac{z\gamma(K+1)}{\overline{Y}}\right)/\zeta!\right) \\ \times e^{\left(-\vartheta_I - \frac{(\vartheta_I+1)(z-1)}{\bar{Z}}\right)} I_0\left(2\sqrt{\frac{K(K+1)(z-1)}{\bar{Z}}}\right) dz. \end{aligned} \tag{2.76}$$

P_{outage} can be given as,

$$P_{outage} = P(\gamma_R < \gamma_{th}) = F_{\gamma_R}(\gamma_{th}) \tag{2.77}$$

P_{ef} can be written as

$$\begin{aligned} P_{ef} &= 1-(1-P_{outage})^B \\ &= 1-\Big[1-\frac{2(\vartheta_I+1)e^{-K}}{\bar{Z}^2} \\ \times \int_0^\infty (z-1)&\left(\sum_{\zeta=0}^\infty (K)^\zeta \Gamma\left(1+\zeta, \frac{z\gamma_{th}(K+1)}{\overline{Y}}\right)/\zeta!\right) \\ \times e^{\left(-\vartheta_I - \frac{(\vartheta_I+1)(z-1)}{\bar{Z}}\right)} &I_0\left(2\sqrt{\frac{K(K+1)(z-1)}{\bar{Z}}}\right) dz\Big]^B. \end{aligned} \tag{2.78}$$

2.3.1.4 Error Rate Analysis

The mathematical expression for the average symbol error rate (SER) by using form of $\bar{P}_{ser} = \phi Q(\sqrt{2\chi\gamma})$. Here, $Q(.)$ denotes Gaussian Q-function. For M-PSK modulation ϕ and χ expressions are $\phi = 2$ and $\chi = \sin^2(\pi/M)$. M denotes modulation order. Average SER expression can be calculated [73]

$$\bar{P}_{ser} = \frac{\phi\sqrt{\chi}}{2\sqrt{\pi}} \int_0^\infty \frac{1}{\sqrt{\gamma}} e^{(-\chi\gamma)} F_{\gamma_R}(\gamma) d\gamma. \tag{2.79}$$

The moment generation function (MGF) $M_{\gamma_R}(s)$ of SINR at R can be obtained as

$$M_{\gamma_R}(s) = E[e^{-s\gamma}] = 1 - s\int_0^\infty F_{\gamma_R}(\gamma) e^{-s\gamma} d\gamma. \tag{2.80}$$

For M-QAM modulation is $\phi = (\sqrt{M}-1)/\sqrt{M}$ and $\chi = 3/(2(M-1))$. Thus, average SER for M-QAM modulation type can be expressed as [73]

$$\begin{array}{c} \bar{P}_{ser} = \frac{4}{\pi}\phi \int_0^{\pi/2} M_{\gamma_R}\big(s = \frac{\chi}{\sin^2\theta}\big)d\theta \\ -\frac{4}{\pi}\phi^2 \int_0^{\pi/4} M_{\gamma_R}\big(s = \frac{\chi}{\sin^2\theta}\big)d\theta. \end{array} \tag{2.81}$$

Average SER might be approximated with reference to average bit error rate (BER) $\bar{P}_{ber}$ which is defined as [73]

$$\bar{P}_{ber} \approx \bar{P}_{ser}/\log_2 M. \tag{2.82}$$

2.3.1.5 Throughput Analysis

The throughput S for safety messages (sm) as well as non-safety data (nsd) can be given as

$$S_{sm} = \frac{P_s P_b (1-P_{ef})L}{(1-P_b)T_{slot} + P_b P_s (1-P_{ef})T_{s-sm} + P_b(1-P_s)T_c + P_b P_s P_{ef} T_{ef}}, \tag{2.83}$$

$$S_{nsd} = \frac{P_s P_b (1-P_{ef})L}{(1-P_b)T_{slot} + P_b P_s (1-P_{ef})T_{s-nsd} + P_b(1-P_s)T_c + P_b P_s P_{ef} T_{ef}}. \tag{2.84}$$

2.3.1.6 Delay Analysis

Time duration from the creation of a frame to its successful transmission is frame delay. Let $E[D]$ be frame delay which can be written as:

$$E[D] = E[C_F](E[D_b] + T_c + T_w) + (E[D_b] + T_s), \tag{2.85}$$

where $E[C_F]$ denotes mean number of collisions of a frame until successful transmission, $E[D_b]$ represents backoff delay that is the backoff of a vehicle before accessing the channel, and T_w is waiting time of a vehicle to sense the channel again after a collision. T_w can be written as

$$T_w = SIFS. \tag{2.86}$$

$E[C_F]$ can be obtained from probability of successful transmission P_s. Since average number of retransmission for a successful transmission is $1/P_s$,

$$E[C_F] = \frac{1}{P_s} - 1. \tag{2.87}$$

$E[D_b]$ depends on backoff counter value and paused time of counter when channel is busy. If backoff counter at b_{bc} and to reach 0, b_c slot times is needed without considering pause of counter. The average of this time interval can be written as

$$\begin{aligned} E[X] = \sum_{b_c=0}^{CW-1} b_c b_{b_c} = \sum_{b_c=0}^{CW-1} b_c \tfrac{CW-b_c}{CW} b_0 \\ = \tfrac{(CW-1)(CW+2)}{(CW+1)}. \end{aligned} \tag{2.88}$$

Let $E[SC_f]$ be average time a vehicle counter freeze, $E[N_{SC_f}]$ be average number of times that a vehicle senses transmission from other vehicles before the backoff counter becomes 0, and $E[\varphi]$ be average number of sequential idle times before a transmission occurs. The relationship can be calculated as

$$E[N_{SC_f}] = \frac{E[X]}{\max(E[\varphi],1)} - 1, \tag{2.89}$$

$$E[SC_f] = E[N_{SC_f}](P_s T_s + (1-P_s)T_c), \tag{2.90}$$

$$E[\varphi] = \frac{1}{P_b} - 1 \tag{2.91}$$

By using (2.88) to (2.91), $E[D_b]$ can be expressed as

$$E[D_b] = E[X] + E[N_{SC_f}](P_s T_s + (1-P_s)T_c). \tag{2.92}$$

T_s and T_c can be calculated by using eq. (2.58) to (2.60). Therefore, $E[D]$ can be obtained by substituting eqs. (2.86), (2.87), and (2.92) into eq. (2.85).

2.3.2 Numerical Results

The performance of IEEE 802.11p MAC for VANETs with capture effect and channel fading is investigated and analytical study is verified in this section. Numerical results are conducted in MATLAB and Mathematica. We assume two lane road and velocity of vehicles are nearly same. Table 2.4 provides value of parameters utilized in the numerical results. We assume that signal-to-noise ratio (SNR) is: $\overline{Y} = \frac{\sigma_R}{\sigma_{Noise}}$.

Fig. 2.16 shows throughput against number of vehicles (N). Throughput increases with N until a certain stage because fewer N would not cause collision. However, further increase of N will reduce throughput due to additive packets contention for transmission from additive number of vehicles which will make channel busy probability and increase collision probability. It can be seen that sm have higher throughput than nsd because sm are broadcast without any other control

Table 2.4 Value of parameters used in numerical analysis

Parameters	**Value**
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ μs	20, 10, 50 ,1
RTS, CTS, L_h, L (sm), L (nsd), ACK (bytes)	26, 20, 50, 300, 500, 14
R_c, R_d (Mbps)	1, 11
CW, m_r	64, 7
G_r, G_t	1, 1
N, r_t (m)	2-100, 500
σ_R, σ_{Noise}, γ_{th}, z_o (dB)	10, -50, 5, 6-24
D_t (veh/m), v (km/h)	0.01, 0-100
f (GHz), α	5,3

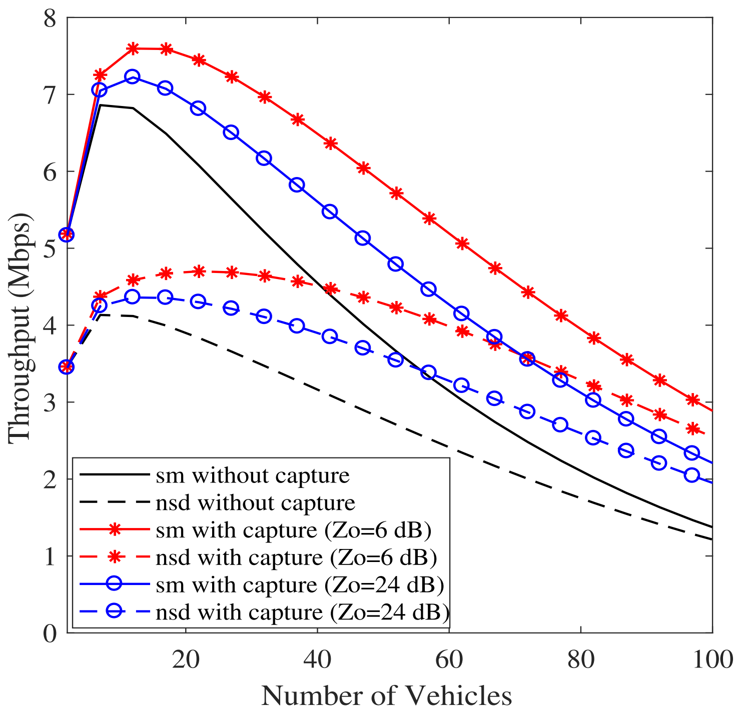

Figure 2.16 Throughput against number of vehicles

message broadcast and nsd is transmitted after WSA broadcast. Throughput with capture is significantly higher than throughput without capture. In the case of concurrent transmission, probability of successful transmission is higher due to capture effect. Since capture increases successful transmission probability, capture increases throughput. Moreover, throughput becomes high if capture threshold is low. Throughput of $z_o = 6$ dB is higher than $z_o = 24$ dB because capture probability becomes low when there is high capture threshold.

Fig. 2.17 shows throughput against probability of errored frame (P_{ef}). Throughput is decreasing with increase of P_{ef} because increasing P_{ef} increases the probability

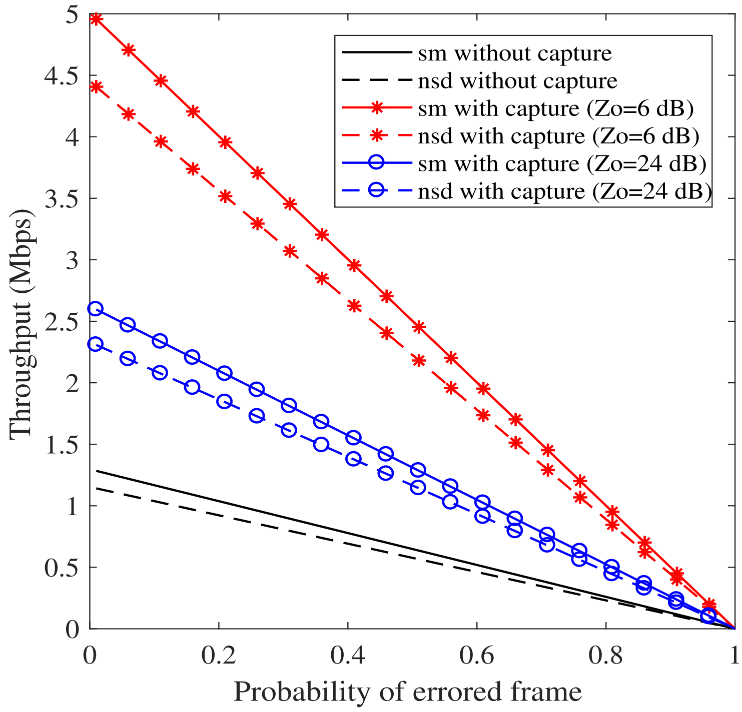

Figure 2.17 Throughput versus probability of errored frame

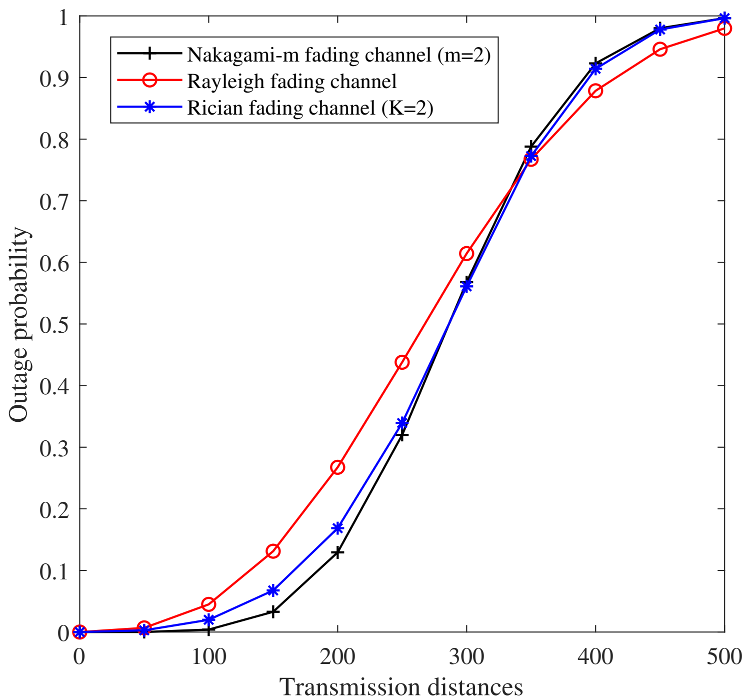

Figure 2.18 Outage probability versus transmission distances

of unsuccessful transmission. sm has higher throughput than nsd for both capture thresholds and without capture. Capture increases successful transmission probability that improves throughput. Moreover, throughput is high for lower value of capture threshold thanks to having higher capture.

Fig. 2.18 illustrates outage probability versus distance for different fading channel models. When distance increases, outage probability increases. If distance is short, Rayleigh fading channel has higher outage probability than Rician fading channel ($K = 2$) and Nakagami fading-m channel ($m = 2$) has lowest outage probability. If distance is long, more than 350 m, then Rayleigh fading channel has lowest outage probability and highest outage probability belongs to Nakagami fading-m channel ($m = 2$), and Rician fading channel ($K = 2$) has slightly lower outage probability than Nakagami fading-m channel ($m = 2$).

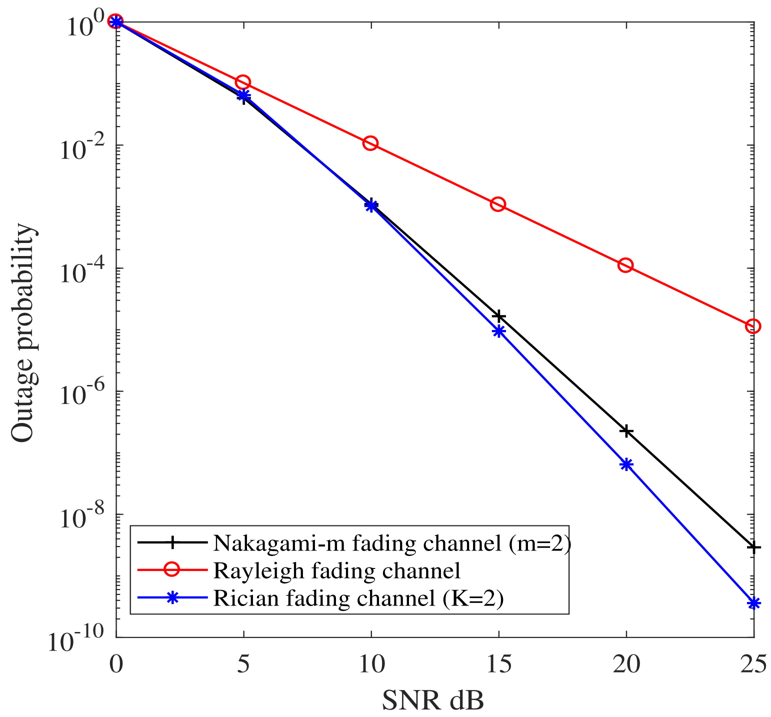

Figure 2.19 Outage probability versus SNR

Figure 2.19 shows outage probability of proposed system versus SNR. Outage probability decreases with increase of SNR for all fading channels. Since signal strength increases with increase of SNR, probability of outage decreases. The system using Rayleigh fading channel has highest outage probability and the one using Rician fading channel with $K = 2$ has the lowest outage probability. The system using Nakagami-m fading channel with $m = 2$ has slightly higher outage probability than the one using Rician fading channel with $K = 2$.

Figure 2.20 presents packet error frame probability versus the velocity of vehicles. Packet error frame probability increases with increase of velocity. When velocity of vehicle increases, network topology changes hastily which makes communication

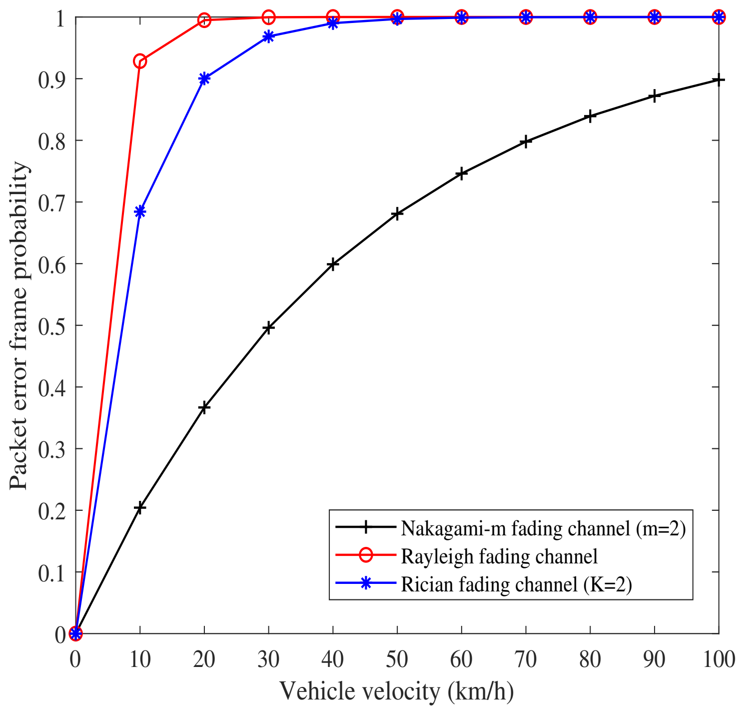

Figure 2.20 Packet error frame probability versus vehicle velocity

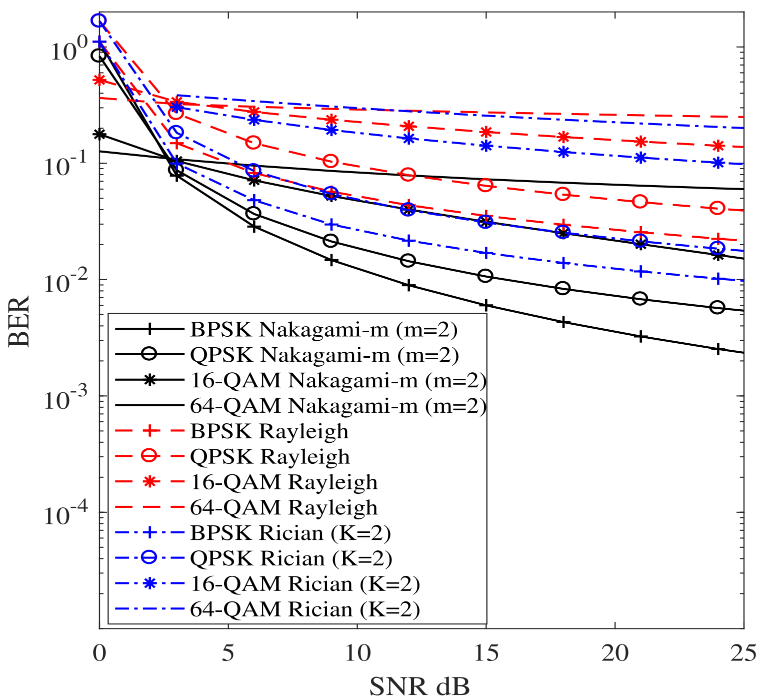

Figure 2.21 BER versus SNR

unstable that results in increment of packet error frame probability. The system using Nakagami-m fading channel ($m = 2$) has the lowest packet error frame probability and the one using Rayleigh fading channel has the highest packet error frame probability.

The system using Rician fading channel ($K = 2$) has slightly lower packet error frame probability than the one using Rayleigh fading channel when vehicle velocity is low but when the velocity is high ($v > 50$), Rician fading channel ($K = 2$) and Rayleigh fading channel have almost packet error frame probability.

Figure 2.21 presents average BER versus SNR. System performance increases with increasing SNR. Thus, the BER falls. For each modulation method, the performance of system using Nakagami-m fading channel is better than one using Rayleigh and Rician fading channel types. The performance of system using Rician fading channel is better than one using Rayleigh fading channel. Nakagami-m fading channel has the lowest BER against SNR where Rayleigh fading channel has the highest for each modulation process. For each channel fading model, BER against SNR is BPSK $<$ QPSK $<$ 16-QAM $<$ 64-QAM. Increasing modulation order M, increases BER, i.e. performance deteriorates.

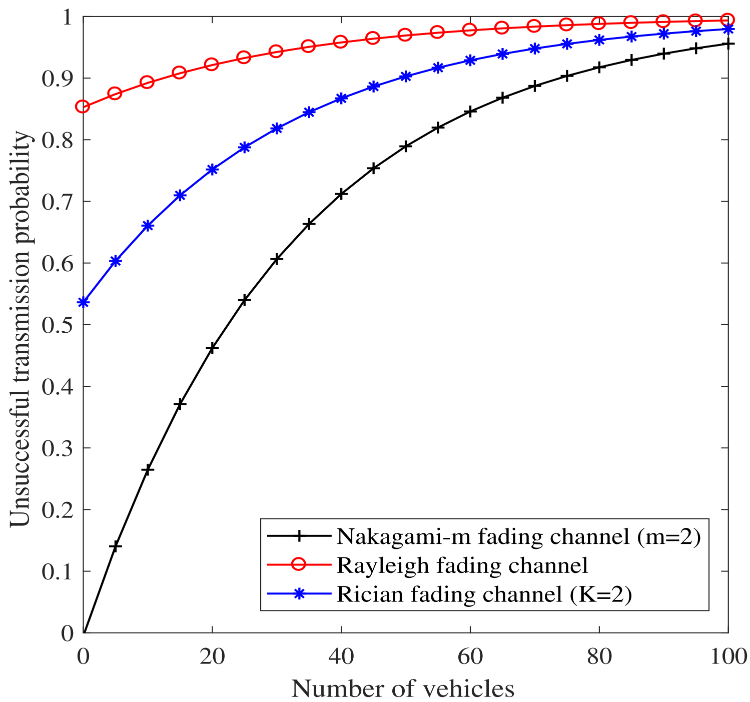

Figure 2.22 Unsuccessful transmission probability versus number of vehicles (z_0=6 dB)

Figure 2.22 demonstrates unsuccessful transmission probability versus number of vehicles (N). Unsuccessful transmission probability increases with increase of N for all fading channels. More packets will compete for transmission with increase of N which will increase collision probability. When the collision probability increases, unsuccessful transmission probability increases too. The system using Rayleigh

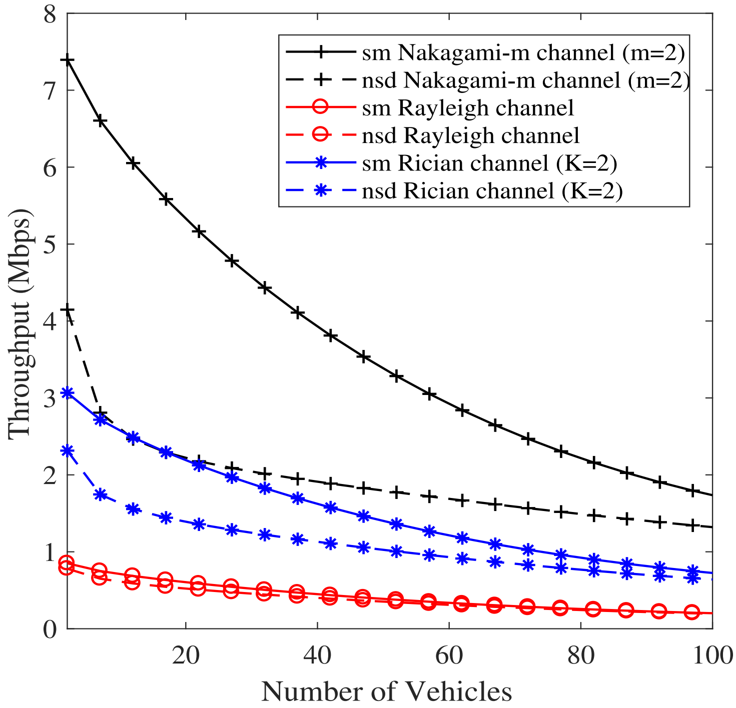

Figure 2.23 Throughput versus number of vehicles under different faded channels (z_0=6 dB)

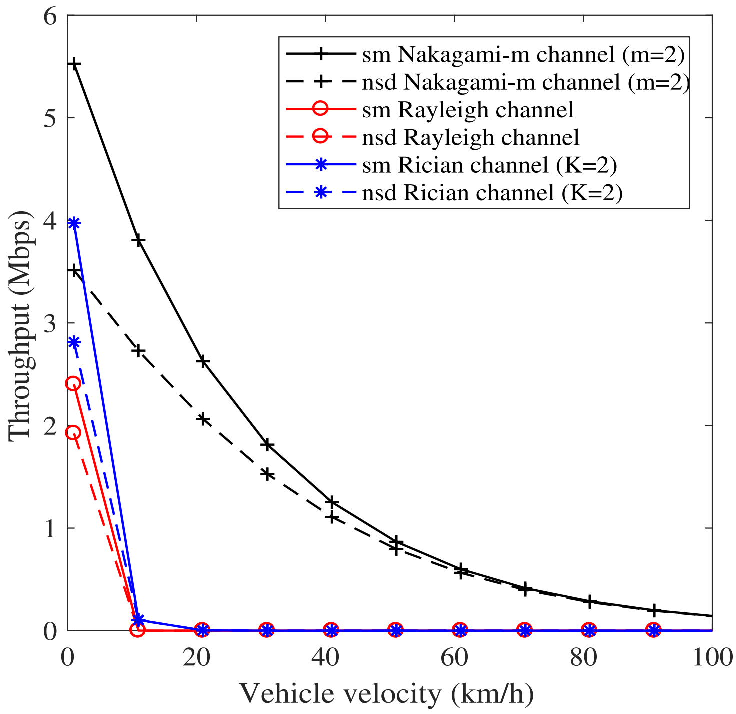

Figure 2.24 Throughput versus vehicle velocity

fading channel has the highest unsuccessful transmission probability and the one using Nakagami fading-m channel ($m = 2$) has the lowest unsuccessful transmission probability. The system using Rician fading channel ($K = 2$) has lower unsuccessful transmission probability than the one using Rayleigh fading channel. Though the difference among different fading channels for unsuccessful transmission probability is high when N is low, when N is high the difference among different fading channels for unsuccessful transmission probability is very low.

Figure 2.23 depicts throughput versus number of vehicles (N) for different channel models. For all fading channels throughput decreases with increase of N. When N increase, more packets will arrive from additional vehicles which will increase number of packets contend for transmission. Extra packet transmission with increase of N will increase collision probability which degrades throughput. System using Rayleigh fading channel has the lowest throughput and the one using Nakagami fading-m channel ($m = 2$) has the highest throughput. The system using Rician fading channel ($K = 2$) has higher throughput than the one using Rayleigh fading channel.

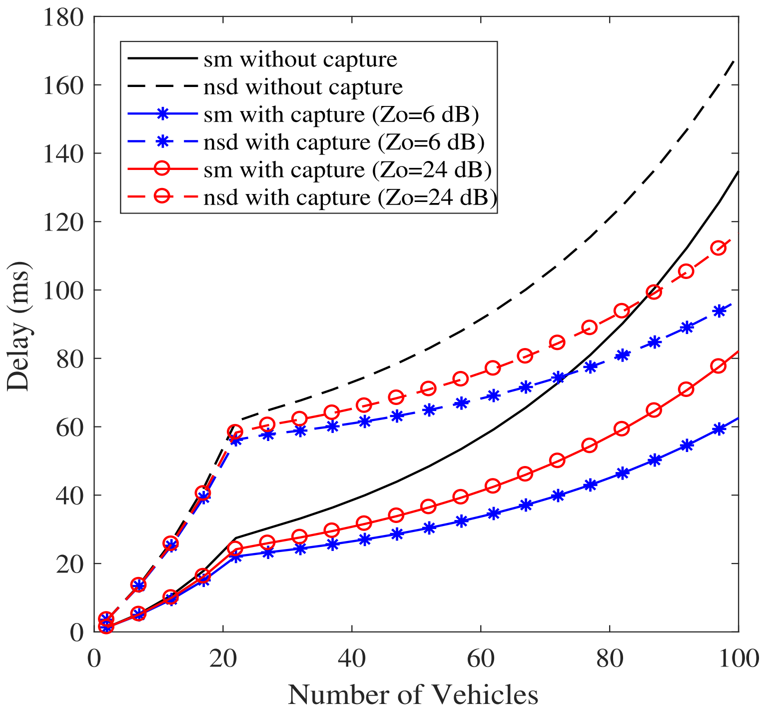

Figure 2.25 Average delay versus number of vehicles

Figure 2.24 illustrates throughput against vehicle velocity for different channel fading models. Throughput decreases with increase of vehicle velocity. Mobility of vehicle causes rapid topology changes with frequent link breakage which makes communications unstable because of collision and packet loss. Throughput is highest under Nakagami-m fading channels. The system using Rician fading channel ($K = 2$ and Rayleigh fading channel have the same throughput when velocity is more than

20 km/h. When velocity is less than 20 km/h, the system using Rician fading channel ($K = 2$) has higher throughput than the one using Rayleigh fading channel.

Figure 2.25 shows average delay versus number of vehicles. The number of packets for transmission will increase with number of vehicles which results in more packets contention. The channel will be busier for more packets contention which will increase collision probability. Therefore, delay increases with number of vehicles. Delay for sm is lower than nsd. When capture threshold is lower, delay is lower and when capture threshold is higher, delay is higher because successful transmission probability increases for lower capture threshold. Therefore, when capture threshold 6 dB, delay is lower than capture threshold of 24 dB for both sm and nsd.

3
Modeling and Performance Analysis of IEEE 802.11

In this chapter, the IEEE 802.11 is modeled and performance is analyzed. The basic access system of IEEE 802.11 is DCF and EDCAF is used for the contention-based prioritized QoS support. IEEE 802.11 DCF is provided in Section 3.2, Section 3.3 details out EDCAF, and Section 3.4 describes the performance under channel fading and capture effect.

3.1 Distributed Coordination Function

In this section, a systematic model is presented to study the impact of IEEE 802.11 MAC for VANETs where both sm and nsd are considered. The main objective of this study to scrutinize the performance of the IEEE 802.11 in VANETs and to check whether the IEEE 802.11 can satisfy the performance criteria for VANETs or not. Performance influencing parameters are taken into account. Markov chain model based analytical study is presented. Probability of collision, probability of successful transmission, throughput, and delay expressions are acquired. Furthermore, the proposed performance model is validated with numerical results and whether the IEEE 802.11 can fulfill the performance criteria for VANETs or not is observed.

3.1.1 Performance Analysis

Same VANET scenario is considered which is mentioned in Section 2.2.1 from eq. (2.1) to eq. (2.6). When a node has a safety message to transmit, first it broadcast RTS, then after receiving CTS, the safety message is broadcast and successful transmission is detected by receiving ACK. To transmit a non-safety data, the sender transmits RTS to the receiver, then the sender send data to the receiver after receiving CTS. After receiving data successfully by the receiver, the receiver send ACK to the sender.

When a vehicle has a packet to transmit, starts to listen the channel. If the channel is listened idle for DCF inter frame space (DIFS) time, the vehicle transmits. Otherwise, the vehicle initiates a random backoff before transmitting to reduce collision because there could be packet transmission by any of the remaining vehicles. Let $b(t)$ and $s(t)$ be the stochastic process which represent the backoff time counter and backoff stage for a vehicular node at time t, respectively where b_c and b_s express the value of the backoff counter and backoff stage, respectively. If m_r and CW symbolize the maximum retransmission limit and contention window size, respectively, then $b_c \in (0, CW_0 - 1)$, $b_s \in (0, m_r)$. The initial value of b_c is uniformly selected from [0, CW_0-1] which can be denoted as $CW_{\min}$. It is decreased by 1 when the channel is listened idle in a slot time, and paused in the existing value when the channel becomes busy, and restarted when the channel is listened idle once more for higher than T_{DIFS}. The packet will be transmitted when b_c is 0. When a collision occurs after transmission, then the b_s will be incremented by 1. CW doubles after each failed transmission and can have the maximum value $CW_{\max} = 2^{m_r} CW_{\min}$. Let P_c and P_b be the probability of collision and channel busy, respectively.

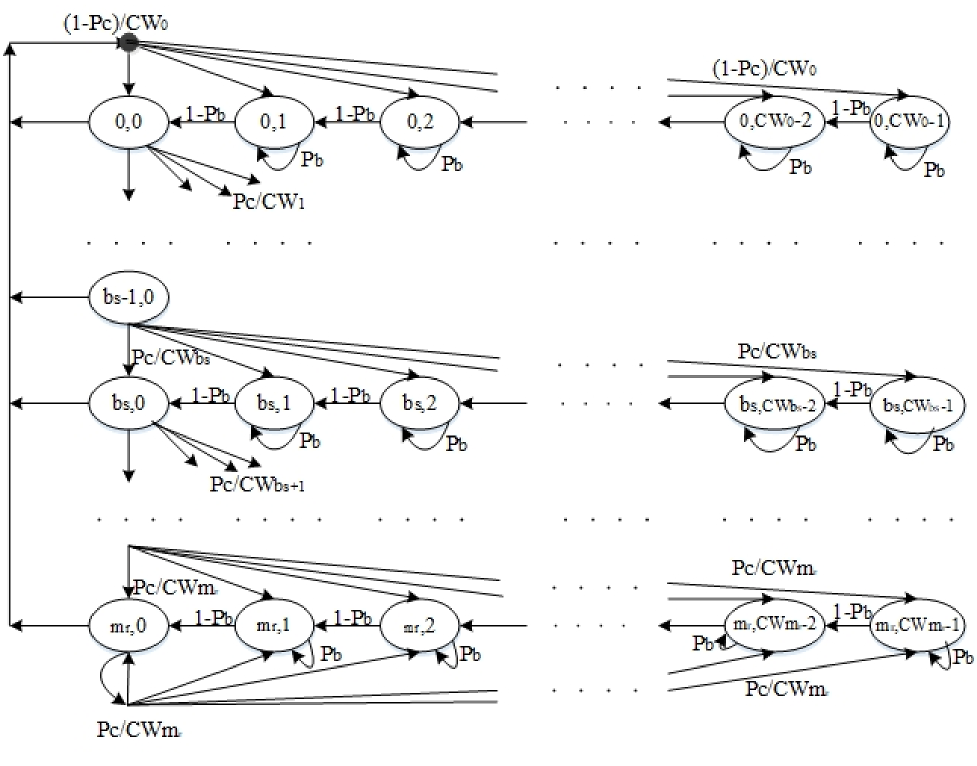

Figure 3.1 Markov chain model for the backoff process

The two dimensional (2D) process $s(t), b(t)$ with the discrete-time Markov chain is demonstrated in Figure 3.1 where

$$P\left[(b_s, b_c)|(b_s, b_c + 1)\right] = 1 - P_b; \left[b_c \in (0, CW_{b_s} - 2),\ b_s \in (0, m_r)\right], \tag{3.1}$$

$$P\left\{0, b_c | b_s, 0\right\} = (1 - P_c)/CW_0;\ [b_c \in (0, CW_0 - 1),\ b_s \in (0, m_r)], \tag{3.2}$$

$$P\left\{b_s, b_c | b_s - 1, 0\right\} = P_c/CW_{b_s};\ \left[b_c \in (0, CW_{b_s} - 1),\ b_s \in (1, m_r)\right], \tag{3.3}$$

$$P\left\{m_r, b_c | m_r, 0\right\} = P_c/CW_{m_r};\ \left[b_c \in (0, CW_{m_r} - 1)\right]. \tag{3.4}$$

The b_c is decreased by 1 if the channel is idle in equation (3.1), equation (3.2) states that b_s starts with 0 and b_c is uniformly taken from [0, CW_0-1] after a successful transmission, b_s is incremented by 1 after a failed transmission in equation (3.3), and b_s is not incremented after it reaches to maximum value in equation (3.4). Let $b_{b_s,b_c} = \lim_{t\to\infty} P\left\{s(t) = b_s, b(t) = b_c\right\}$, $\left(b_s \in (0, m_r), b_c \in (0, CW_{b_s} - 1)\right)$ be the stationary distribution of the Markov chain. Using the Markov chain, the following solution can be attained.

$$b_{b_s,\,b_c} = \frac{CW_{b_s} - k}{CW_{b_s}} b_{b_s,0}. \tag{3.5}$$

Since the sum of all possible states is one,

$$\begin{aligned} 1 &= \sum_{b_s=0}^{m_r} \sum_{b_c=0}^{CW_i-1} b_{b_s,b_c} = \sum_{b_s=0}^{m_r} b_{b_s,0} \sum_{b_c=0}^{CW_{b_s}-1} \tfrac{CW_{b_s}-k}{CW_{b_s}} = \sum_{b_s=0}^{m_r} b_{b_s,0} \tfrac{CW_{b_s}+1}{2} \\ &= \tfrac{b_{0,0}}{2}[CW(\sum_{b_s=0}^{m_r-1} (2P_c)^{b_s} + \tfrac{(2P_c)^{m_r}}{1-P_c}) + \tfrac{1}{1-P_c}]. \end{aligned} \tag{3.6}$$

So,

$$P\left\{m_r, b_c | m_r, 0\right\} = P_c/CW_{m_r};\ \left[b_c \in (0, CW_{m_r} - 1)\right]. \tag{3.7}$$

Let P_t be the probability of a packet transmission in an arbitrarily slot time that can occur when b_c becomes 0 regardless of b_s, which can be obtained as

$$P_t = \sum_{b_s=0}^{m_r} b_{b_s,0} = \frac{b_{0,0}}{1 - P_c} = \frac{2(1 - 2P_c)}{(1 - 2P_c)(CW + 1) + P_c CW(1 - (2P_c)^{m_r})}. \tag{3.8}$$

When $m_r = 0$,

$$P_t = \frac{2}{CW + 1}. \tag{3.9}$$

When $P_c = \frac{1}{2}$,

$$P_t = \frac{2}{1 + CW + m_r CW/2}. \tag{3.10}$$

P_b, P_c, P_s, $P_{parrival}$, and T_e can be obtained from eq. (2.14), (2.15), (2.16), (2.19), (2.20), respectively. T_s, and T_c for sm and nsd can be written as

$$T_{s-sm} = T_{DIFS} + 3T_{SIFS} + (N-1)T_{RTS} + (N-1)T_{CTS} + \frac{(N-1)L}{R_d} + (N-1)T_{ACK} + T_{delay}, \quad (3.11)$$

$$T_{s-nsd} = T_{DIFS} + 3T_{SIFS} + T_{RTS} + T_{CTS} + \frac{L}{R_d} + T_{ACK} + T_{delay}, \quad (3.12)$$

$$T_c = T_{DIFS} + T_{SIFS} + T_{RTS} + T_{delay}, \quad (3.13)$$

where $T_{SIFS}, T_{DIFS}, T_{RTS}, T_{CTS}$ and T_{ACK} are length of time for short inter frame space (SIFS), DIFS, RTS, CTS, and acknowledgment (ACK), respectively. L, R_d, and T_{delay} denote packet size, transmission rate, and propagation delay, respectively.

Throughput S for sm and nsd can be obtained from eq. (2.25) and (2.26), respectively.

A packet will be dropped if it is failed to retransmit after the maximum retransmission limit. Therefore, the packet dropping rate (PDR) can be expressed as

$$PDR = (1 - P_{suc})^{m_r}. \quad (3.14)$$

$E[D]$ can be obtained from eq. (2.34) to (2.35).

3.1.2 Numerical Results

This section assesses the performance of IEEE 802.11 MAC for VANETs for sm and nsd as well as ascertains the analytical study. The numerical analysis is performed in the MATLAB. Two lane road with 5 m width each is considered. We assume that vehicles are running with nearly the same velocity. Table 3.1 presents the value of parameters utilized in the numerical analysis.

Table 3.1 Value of parameters utilized in numerical analysis

Parameters	**Value**
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ μs	20, 10, 50 ,1
RTS, CTS, L_h, L, ACK (bytes)	26, 20, 50, 512, 14
R_c,R_d (Mbps)	1, 11
CW	64
m_r	7
N (m)	0-100
r_t (m)	500
D_T (veh/m)	0.01
v (km/h)	100

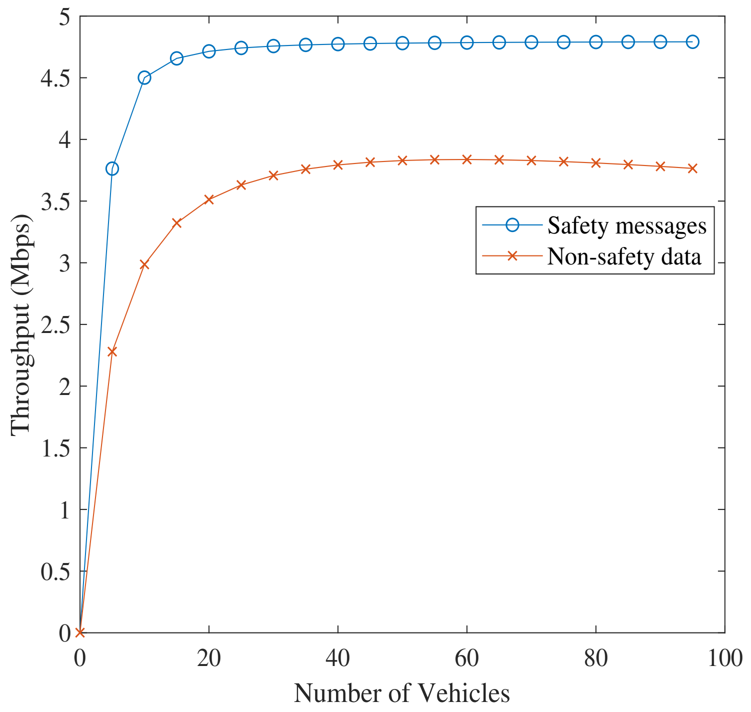

Figure 3.2 Throughput against number of vehicles

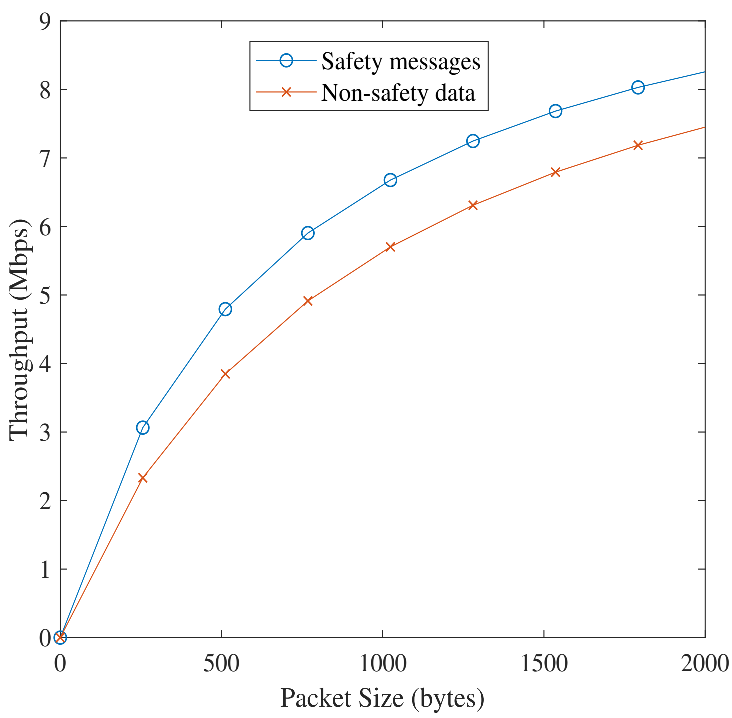

Figure 3.3 Throughput against packet size

Figure 3.2 depicts throughput versus number of vehicles. Throughput increases until a certain point then throughput decreases which can be observed in Figure 3.2. Since fewer number of vehicles may not cause collision, throughput starts to increase with increasing vehicles, but after the number of vehicles in the transmission range further increases, then more vehicles would cause more collisions and throughput falls. Therefore, there is a certain number of vehicles or vehicle density that could provide maximum throughput. To have optimum throughput, a parameter can be optimized based on number of vehicles or vehicle density in the network. From eq. (2.25) and (2.26), throughput is achieved from which it is understandable that throughput depends on transmission probability. From eq. (3.8), it is obvious that transmission probability depends on CW size. Therefore, CW size can be optimized which will adopt the optimum transmission probability that will maximize throughput.

Figure 3.3 illustrates throughput against packet size. Throughput tends to rise with the increase of packet size. Increasing the packet size means increasing the amount of data which increases throughput. Higher proportional protocol header overhead is generated by the small packet size which results in lower throughput. Since the substantial overhead of every frame is spread out over many payload or application bytes, better payload utilization of bandwidth can be accomplished with larger frames. Therefore, throughput rises with the upturn of packet size.

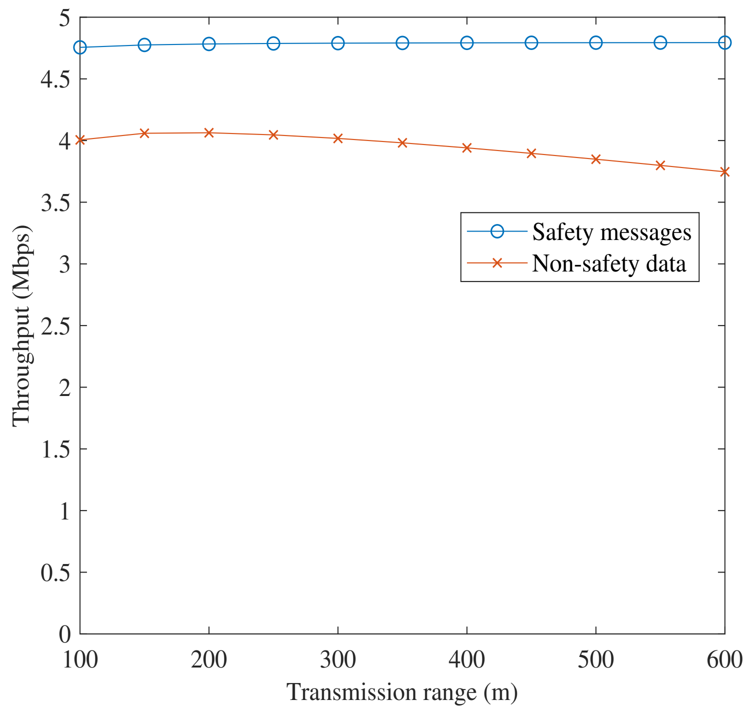

Figure 3.4 Throughput against transmission range

Figure 3.4 demonstrates the throughput against transmission range. Higher throughput can be achieved with smaller transmission range but the network can be disconnected with too small transmission range. Figure 3.5 shows the throughput against vehicle velocity. Since high vehicles mobility can results in rapid topology changes with frequent link breakage which causes unstable communications due to collision and packet loss, the throughput is decreasing with the increment of vehicles velocity. The number of vehicular nodes is 100 in Figures 3.3, 3.4, and 3.5. It is also noticeable that the throughput of highest priority safety messages is higher than lowest priority non-safety data.

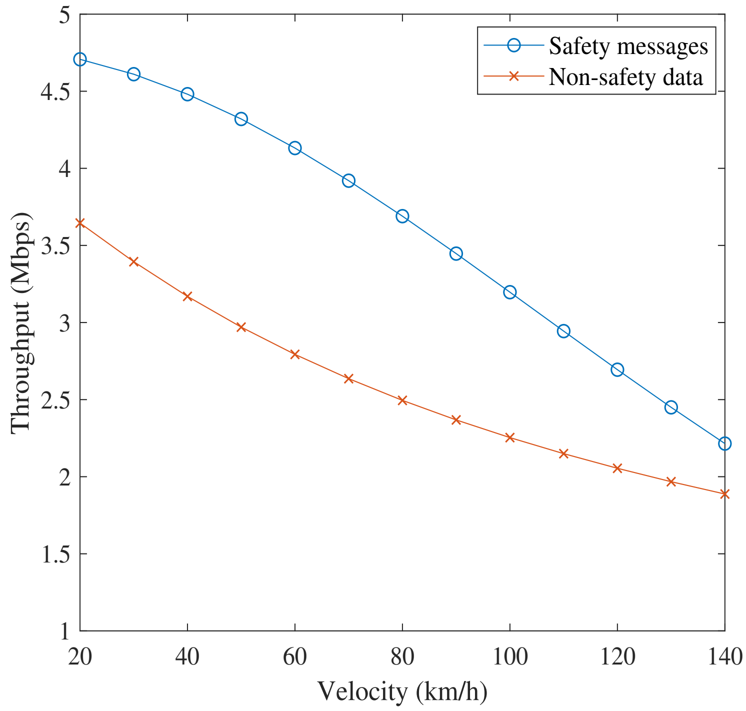

Figure 3.5 Throughput against velocity

Figure 3.6 shows PDR versus number of vehicles. PDR is increased with number of vehicles and if contention window is large, the PDR is less because large conetention window size CW decreases the probability of collision. The reliability of data transmission depends on PDR. If PDR is less, then the reliability of transmission is high.

Figure 3.7 presents the average delay against number of vehicles. Since the increment of number of vehicles would raise the number of packets to be transmitted, more packets will contend for transmission that will keep channel busy more and the probability of collision will be increased. Therefore, the average delay is growing with the rise of number of vehicles. Though the delay of safety messages is lower than non-safety data, when there is high traffic, the IEEE 802.11 MAC can not fulfils the strict delay requirement of 100 ms for safety messages.

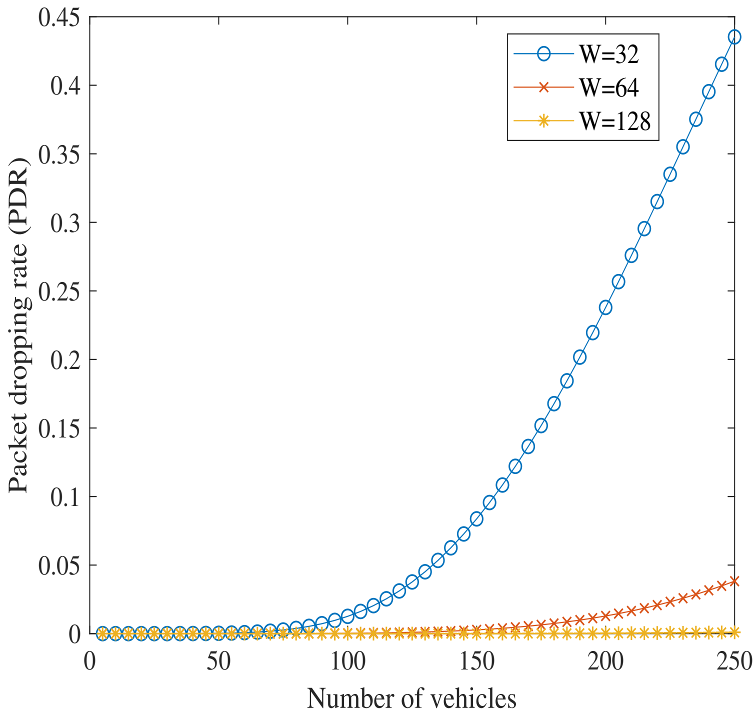

Figure 3.6 PDR against number of vehicles

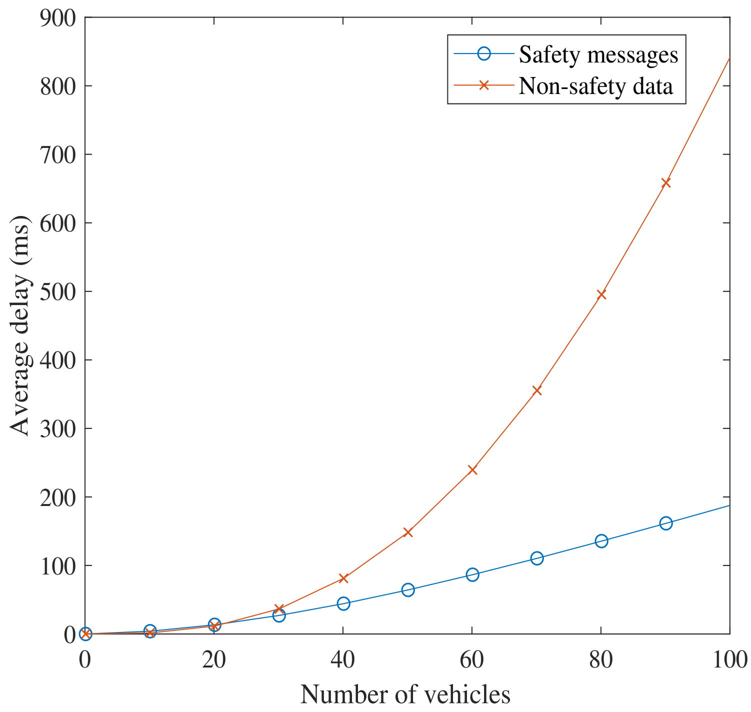

Figure 3.7 Average delay against number of vehicles

3.2 Enhanced Distributed Channel Access Function

In IEEE 802.11, DCF does not differentiate among different types of traffics. On the other side, the IEEE 802.11 EDCAF supports QoS among different traffic types. EDCA parameters for each AC is given Table 2.2. In IEEE 802.11 EDCAF, while packets arrive at the MAC layer, it uses 8 user priorities (UPs) which ranges from 0 to 7 with 7 having the highest priority. UPs are distributed among 4 different first-in first-out (FIFO) queues termed as access categories (ACk) (k = 0,1,2,3). UP-to-AC mappings are presented in Table 3.2. The prioritization method within each vehicle is presented in Figure 2.7.

Table 3.2 User priority (UP)-to-access category (AC) mappings

Priority	UP	AC	Traffic Type
Lowest	1	AC_BK	Background
	2	AC_BK	Background
	0	AC_BE	Best effort
↓	3	AC_BE	Best effort
	4	AC_VI	Video
	5	AC_VI	Video
	6	AC_VO	Voice
Highest	7	AC_VO	Voice

For the different ACs, there are four transmission queues and four distinct EDCAF. Since the EDCA parameters is not same for each AC, each AC queue employs distinct AIFS, CW_{min}, and CW_{max}. To implement priority of the transmission, EDCAF uses arbitration inter-frame space (AIFS) which is a new inter frame space (IFS). T_{AIFS}[AC] can be given from eq. (2.36).

3.2.1 Performance Analysis

Transmission probability P_t can be obtained from eq. (3.8), (3.9), and (3.10), respectively

$$P_t = \sum_{b_s=0}^{m_r} b_{b_s,0} = \frac{b_{0,0}}{1-P_c} = \frac{2(1-2P_c)}{(1-2P_c)(CW[AC]+1)+P_cCW[AC](1-(2P_c)^{m_r})}. \quad (3.15)$$

When $m_r = 0$,

$$P_t = \frac{2}{CW[AC]+1}. \quad (3.16)$$

When $P_c = \frac{1}{2}$,

$$P_t = \frac{2}{1+CW[AC]+m_rCW[AC]/2}. \quad (3.17)$$

P_b, P_c, P_s, $P_{parrival}$, and T_e can be obtained from eq. (2.14), (2.15), (2.16), (2.19), (2.20), respectively. T_s and T_c can be given as

$$T_s = T_{AIFS}[AC] + 3T_{SIFS} + T_{RTS} + T_{CTS} + \frac{L}{R_d} + T_{ACK} + T_{delay} \tag{3.18}$$

$$T_c = T_{AIFS}[AC] + T_{SIFS} + T_{RTS} + T_{delay} \tag{3.19}$$

where T_{CTS}, T_{RTS} and T_{ACK} are time period for CTS, RTS, and ACK respectively. L, R_d, and T_{delay} denote size of data, the rate of data transmission and time duration of propagation delay respectively.

Throughput S and PDR expressions can be obtained from eq. (2.41) and eq. (3.14), respectively. Average delay $E[D]$ can be given from eq. (2.27) as

$$E[D] = E[T_{interval}] - E[P_{drop}]E[T_{drop}]. \tag{3.20}$$

$E[T_{interval}]$, $E[P_{drop}]$, and $E[T_{drop}]$ can be obtained from eq. (2.45), (2.30), and (2.46), respectively where $E[X_{drop}]$ can be written as

$$E[X_{drop}] = \frac{2}{1 + CW\,[\mathrm{AC}] + m_r CW\,[\mathrm{AC}]/2}. \tag{3.21}$$

Therefore, using equation from (2.45) to (2.46), (2.30), and (3.21) in (3.20) $E[Delay]$ can be given as

$$E[D] = T_e\left(N - \frac{P_{drop}}{1 - P_{drop}} \times \frac{2}{1 + CW\,[\mathrm{AC}] + m_r CW\,[\mathrm{AC}]/2}\right). \tag{3.22}$$

3.2.2 Numerical Results

The performance of IEEE 802.11 EDCAF for VANETs is evaluated in this section. Simulation is conducted in the MATLAB. Two lanes road is taken into consideration. Vehicles are randomly distributed. Table 3.3 provides the parameter values utilized in the numerical results.

The throughput contrary to the number of vehicles for different ACs is shown Figure 3.8. The throughput is going up with increment of the number of vehicles until a definite range which would not create collision. After that throughput starts to decrease because with the increment of further number of vehicles more packets will compete in the AC queue for transmission which will create more collisions.

Figure 3.9 shows the throughput against vehicle velocity for different ACs. With the

Table 3.3 Parameter values used in numerical results

Parameters	**Value**
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ μs	20, 10, 64 ,1
RTS, CTS, ACK (bytes)	26, 20, 14
L, L_h (bytes)	1024, 50
R (m)	500
β (veh/m)	0.01
v, v_f (km/h)	10-80, 160
J_T (veh/km/lane)	120
N (m)	0-100
R_d (m)	11
m_r	7
$CW_{min}[0], CW_{min}[1], CW_{min}[2], CW_{min}[3]$	15, 15, 3, 7
$CW_{max}[0], CW_{max}[1], CW_{max}[2], CW_{max}[3]$	7, 15, 1023, 1023
$AIFSN[0], AIFSN[1], AIFSN[2], AIFSN[3]$	2, 3, 6,9

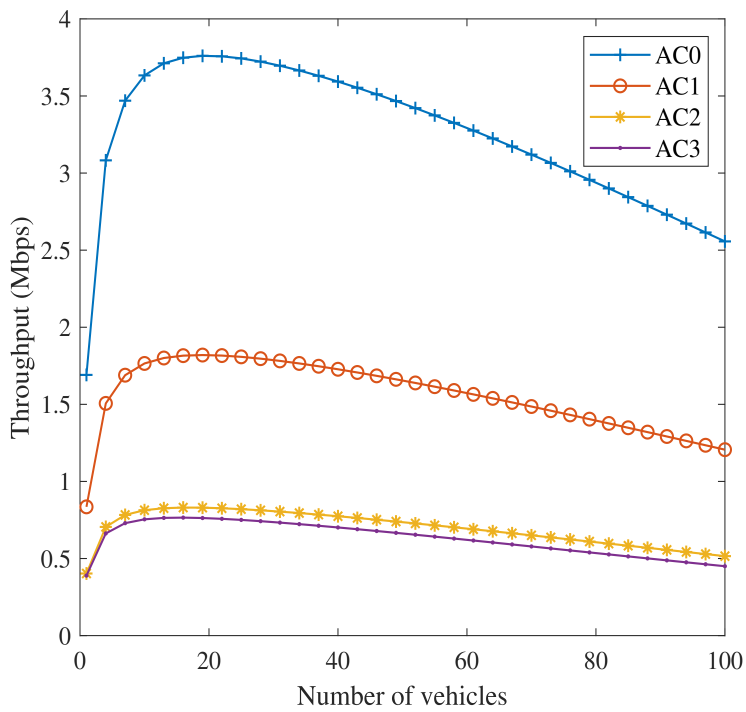

Figure 3.8 Throughput against number of vehicles

increase of the velocity, the throughput is decreasing. Since vehicle mobility can change network topology rapidly which causes collision as well as packet loss. Figure 3.10 shows the throughput against transmission range for different ACs. Throughput initiates to increase with the increase of transmission range. When transmission range increases, communication range increases, then throughput increases. In Figures 3.9 and 3.10 the number of vehicles is 100. In Figures 3.8, 3.9 and 3.10, since AC0 waits less time in the contention due to own EDCA parameters, AC0 has the highest throughput. Then AC1, AC2 and the lowest is AC3.

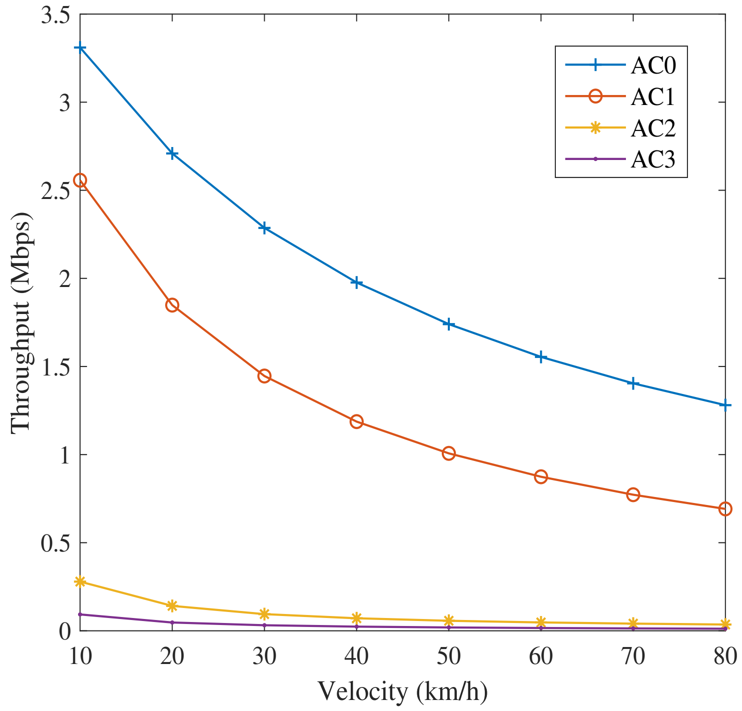

Figure 3.9 Throughput against vehicle velocity

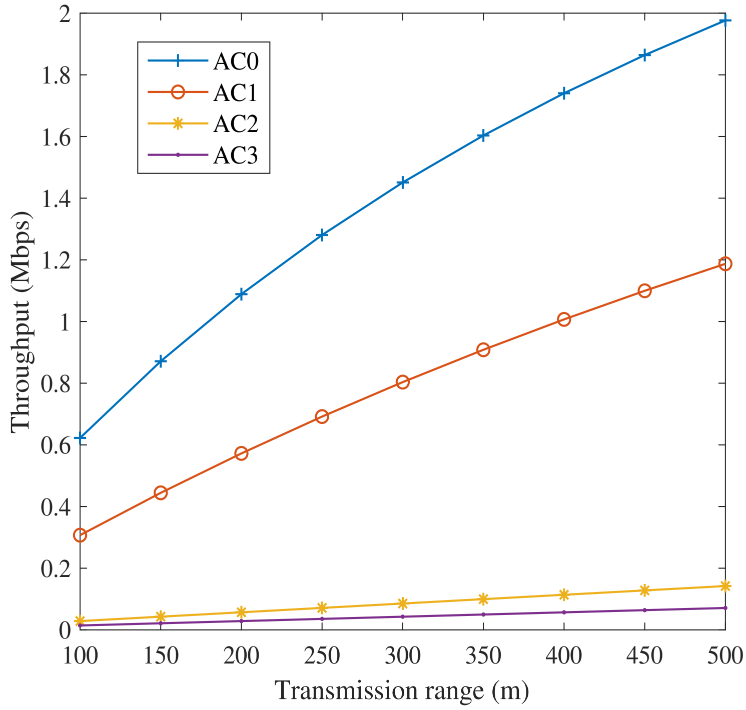

Figure 3.10 Throughput against transmission range

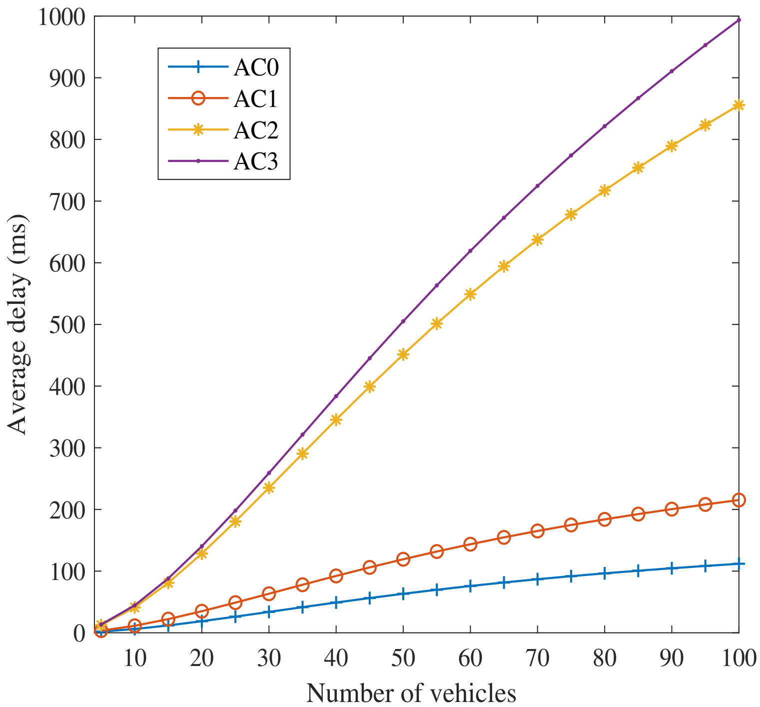

Figure 3.11 Average delay against number of vehicles

Figure 3.11 presents that average delay of each ACs against number of vehicles. The average packet delay upturns with the growth of number of vehicles. As more vehicles in the network will send more packets in the AC queue, contention will be increased which will increase collision probability that results in rises of delay. Besides, it is noticeable that AC0 has the lowest delay whereas AC3 has the highest delay. Delay is increased from AC0 to AC3 due to IEEE 802.11 EDCAF parameters value. Since CW[AC] and AIFSN[AC] is low for AC0, the contention period is less for AC0. Therefore, delay is lowest for AC0. Moreover, CW[AC] and AIFSN[AC] values are increasing from AC0 to AC3 which increase delay from AC0 to AC3. Delay requirement is satisfied for different service requirement by EDCAF parameters.

Figure 3.12 exhibits the PDR against number of vehicles for different ACs. PDR is increasing with the increment of number of vehicles. The reliability of data transmission is contingent to PDR. If PDR is decreasing, then the reliability of transmission is increasing. PDR is high for AC0, then AC1 and AC2, the lowest is AC3. Though AC0 has low delay due to IEEE 802.11 EDCA parameters value, it also increases PDR. As contention period of AC0 is less, it transmit packets more often which increases the probability of collision. However, AC3 has highest contention period which reduces collision probability. When collision probability decreases, the PDR is also decreases.

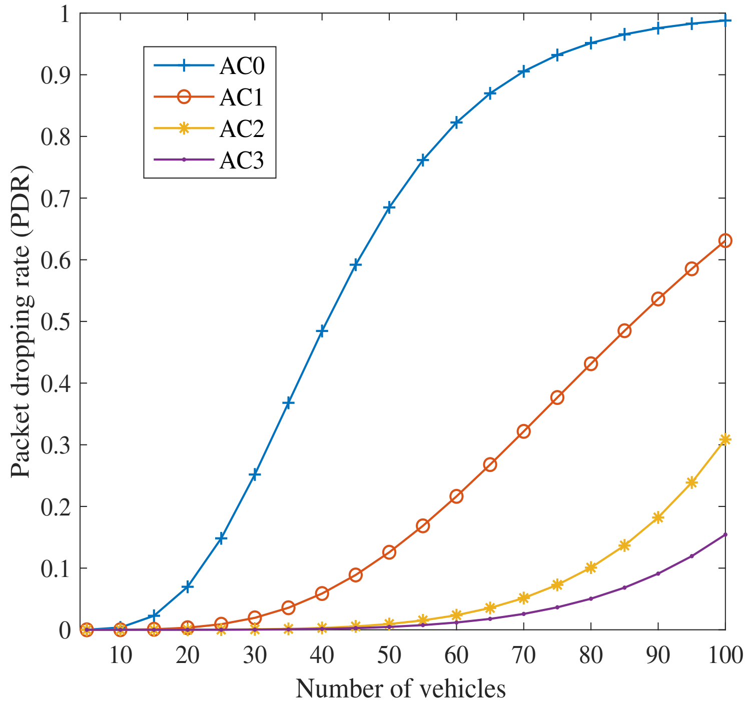

Figure 3.12 PDR against number of vehicles

From Figure 3.8 to Figure 3.11, it is comprehended that throughput of AC0 is higher than AC1, AC1 is higher than AC2, and AC2 is higher than AC3, and in the case of delay AC0 is lower than AC1, AC1 is lower than AC2, and AC2 is lower than AC3. The ACO has highest throughput but lowest delay and AC3 has lowest throughput but highest delay. For throughput, AC0>AC1>AC2>AC3 and for delay, AC0<AC1<AC2<AC3. The backoff process makes it possible. Since T_{AIFS} is different due to different AIFSN value, packets of different ACs have different T_{AIFS}, different ACs have different backoff. AIFSN value of ACO is lowest and AC3 is highest. For AIFSN value, AC0<AC1<AC2<AC3. Not only AIFSN value but also CW_{min} and CW_{max} influence backoff process. The lowest CW_{min} and CW_{max} has AC0 and highest CW_{min} and CW_{max} has AC3. Therefore, due to T_{AIFS}, CW_{min} and CW_{max}, packets in AC0 is transmitted first, then AC1, then AC2, then AC3 which results in highest throughput in AC0 and lowest delay in AC0, and so on.

3.3 Channel Fading and Capture Effect

To assess the performance of the IEEE 802.11 medium access control (MAC) for VANETs under channel fading and capture effect, an analytical model based on Markov chain model is presented. Only Rayleigh fading channel is considered. The relationship among parameters and performance metrics are derived. The probability of successful and unsuccessful transmission, probability of frame capture, and throughput expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented.

3.3.1 Performance Analysis

P_{us} be the unsuccessful transmission probability that a packet transmission is unsuccessful. Unsuccessful transmission can occur due to collision and/or an errored frame due to channel fading and/or noise. If P_{ef} is the probability of errored frame, then P_{us} is

$$P_{us} = 1-(1-P_c)(1-P_{ef}) = P_c + P_{ef} - P_c P_{ef}. \tag{3.23}$$

Practical Rayleigh fading channels are considered. Under Rayleigh fading, the received signal instantaneous envelope is Rayleigh distributed which power is exponentially distributed. The probability density function can be expressed as

$$f_R(y) = \frac{1}{\sigma_R} e^{-\frac{y}{\sigma_R}},\ y > 0, \tag{3.24}$$

where σ_R denotes the local mean power of the transmitted frame at the receiver (R). If d is the distance between the sender (S) and R, then σ_R can be determined by

$$\sigma_R = A d^{-\alpha} \sigma_T, \tag{3.25}$$

where A, α, and σ_T are constant, path-loss exponent, and transmitted signal power, respectively.

A transmitted packet may have interference from concurrent transmission (collision) and background noise. The SINR can be given as

$$\gamma = \frac{\sigma_R^{(0)} |h|^2}{\sigma_{Noise} + \sum_{i=1}^{k} \sigma_R^{(i)} |g_i|^2}, \quad k \in [1, N-1], \tag{3.26}$$

where $\sigma_R^{(0)}$ is the power at the receiver of the transmission, Noise denotes the power of background noise, and $\sigma_R^{(i)}$ is the power of interfering transmissions at the receiver. If there is no collision, i.e. $k = 0$, then the sum equals zero. Under the assumption of power-controlled STAs in infrastructure mode, the probability of capture conditioned on i interfering frames can be expressed as

$$P_{cc}(z_o g(S_f)|i) = P(\gamma > z_o g(S_f)|i) = [1 + z_o g(S_f)]^{-i}, \tag{3.27}$$

$g(S_f)$, P_{Ri}, P_{cap}, and P_s can be attained from eq. (2.52), (2.53), (2.54), and (2.55), respectively. $T_e, T_{s-sm}, T_{s-nsd}, T_c$ and T_{ef} can be achieved from eq. (2.57), (2.58), (2.59), (2.60), and (2.61), respectively.

Throughput S can be obtained for sm as well as nsd from eq. (2.83), and (2.84), respectively.

3.3.2 Numerical Results

This section assesses the performance of IEEE 802.11 MAC for VANETs under channel fading and capture effect as well as ascertains the analytical study. The numerical analysis is performed in the MATLAB. Two lane road with 5 m width each is considered. We assume that vehicles are running with nearly same velocity. Table 3.4 presents the value of parameters utilized in the numerical analysis.

Table 3.4 Value of parameters utilized in numerical analysis

Parameters	**Value**
$T_{slot}, T_{SIFS}, T_{DIFS}, T_{delay}$ μs	20, 10, 50,1
RTS, CTS, L_h, L, ACK (bytes)	26, 20, 50, 512, 14
R_c,R_d (Mbps)	1, 11
CW, m_r	64, 7
N (m)	2-100
r_t (m)	500
β (veh/m)	0.01
v (km/h)	100
z_O (dB)	6, 24

Figure 3.13 depicts throughput versus number of vehicles. Throughput increases until a certain point then throughput decreases which can be observed in Figure 3.13. Since fewer number of vehicles may not cause collision, throughput starts to increase with increasing vehicles, but after the number of vehicular nodes further goes up, then more vehicles would cause more collisions and throughput falls. Capture improves throughput significantly. Capture increases the probability of successful transmission when the channel is accessed simultaneously that results in higher throughput.

Figure 3.14 shows throughput versus number of vehicles for two values of capture thresholds, z_o (6 dB and 24 dB). It is perceptible that the throughput is higher in the case of lower capture threshold value. Since the number of contending stations increase when capture probability is low due to high capture threshold, i.e., for $z_o =$ 24 dB, probability of successful transmission decreases which reduces the throughput.

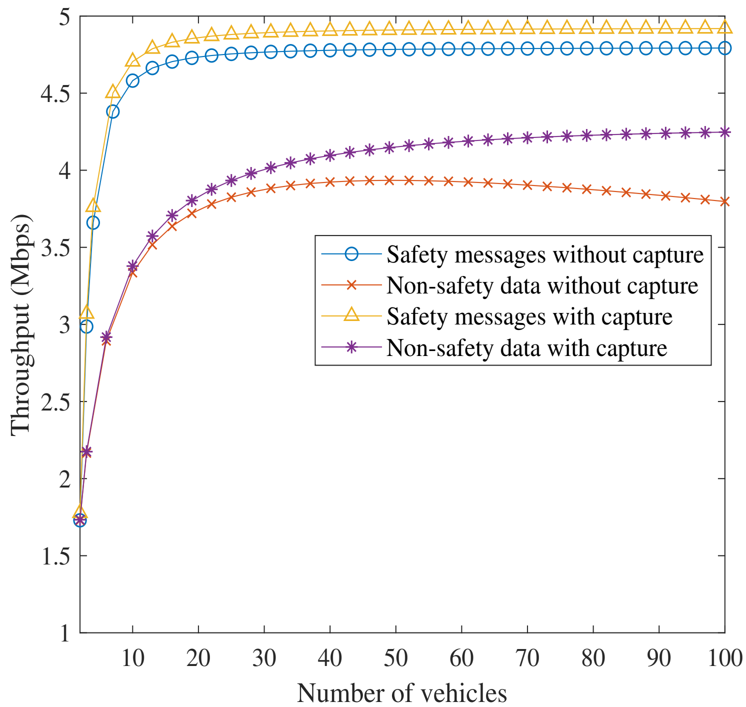

Figure 3.13 Throughput against number of vehicles (L=512 bytes, z_o=6 dB)

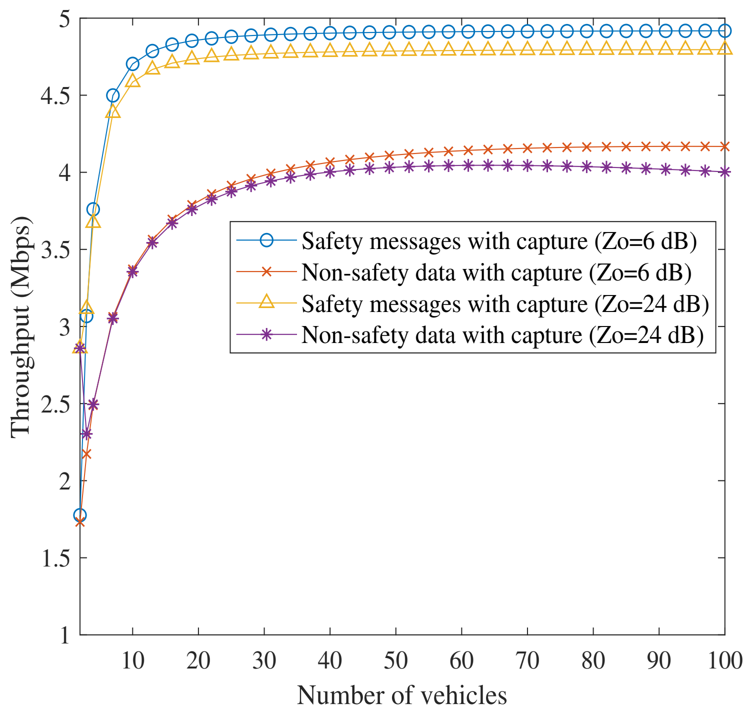

Figure 3.14 Throughput versus number of vehicles (L=512 bytes)

Figure 3.15 demonstrates throughput against packet size. Throughput tends to rise with the enlargement of packet size. Increasing the packet size means increasing the amount of data which increases throughput. Besides, higher proportional

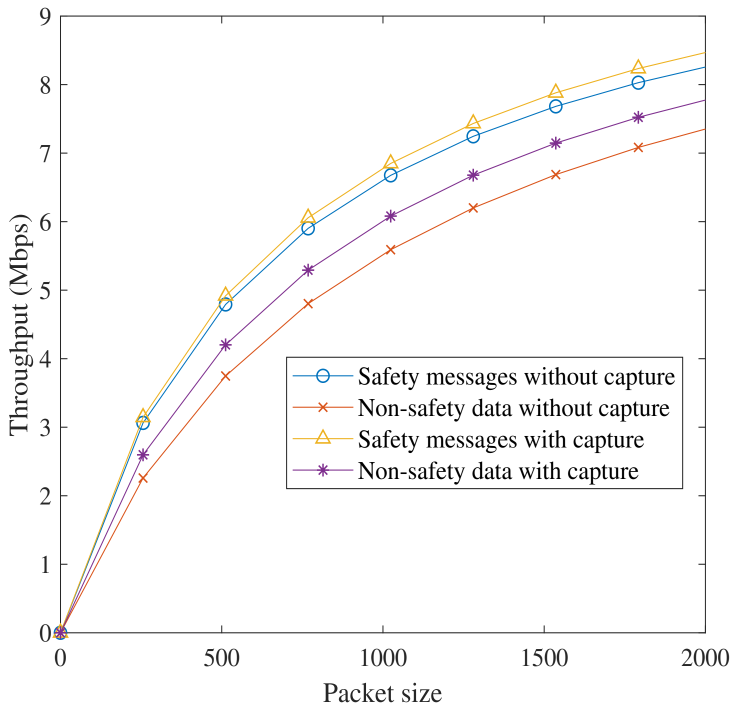

Figure 3.15 Throughput against packet size (L=512 bytes, z_o=6 dB)

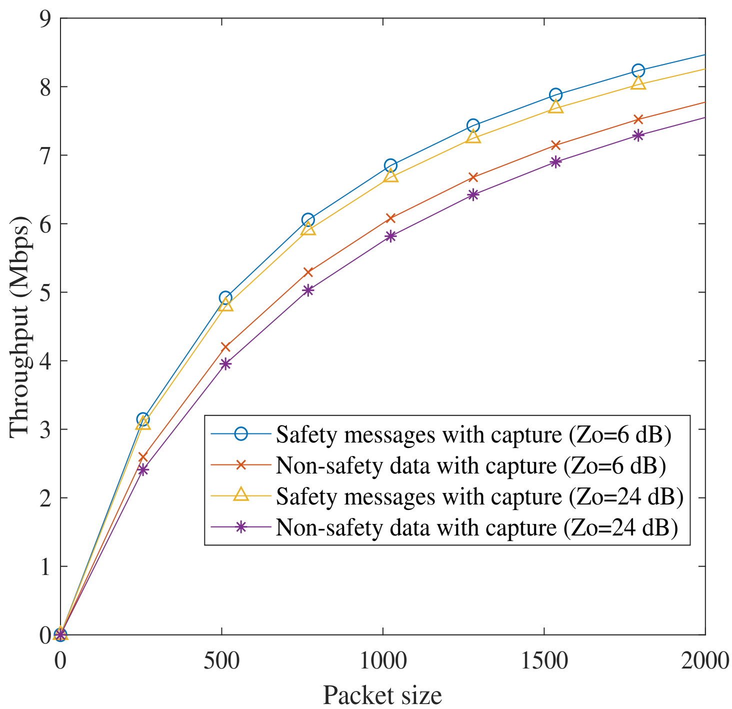

Figure 3.16 Throughput versus packet size (N=100)

protocol header overhead is generated by the small packet size which results in lower throughput. Throughput with capture is always greater than the throughput without capture. Due to capture, the packet with the highest power can be received successfully in the existence of collision which results in increase of throughput.

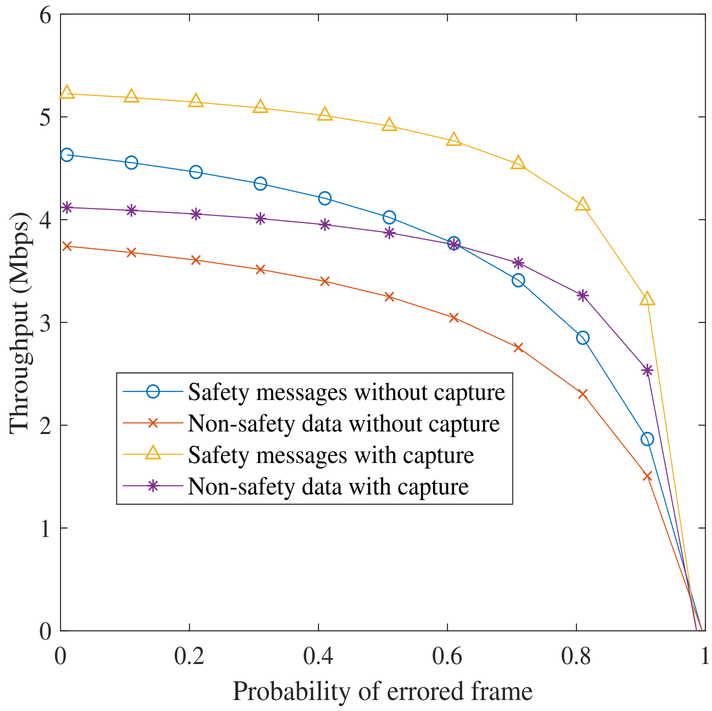

Figure 3.17 Throughput versus probability of errored frame (N=100, L=512 bytes, z_o=6 dB)

Figure 3.16 exhibits throughput versus packet size over two values of z_o (6 dB and 24 dB). Since the substantial overhead of every frame is spread out over many payloads or application bytes, better payload utilization of bandwidth can be accomplished with larger frames. Therefore, throughput rises with the upturn of packet size. If capture threshold is higher, then probability of capture is lower. Alternatively, if capture threshold is low, then capture probability is high which increases the successful transmission probability. Thus, throughput is higher for lower capture threshold. Figures 3.13 to 3.16 is provided for special case when $ef \rightarrow \infty$ and $P_{ef} = 0$. Apparently, due to the "persistent-until-success" retransmission strategy $ef \rightarrow \infty$, there are no frame losses at all.

Figure 3.17 displays throughput versus probability of errored frame. With the increase of probability of errored frame, Pef, throughput is decreasing towards zero. Since the increment of probability of errored frame increases the unsuccessful transmission possibility, throughput decreases with the increase of probability of errored frame. Figure 3.18 illustrates throughput versus probability of errored frame over two values of z_o (6 dB and 24 dB). Throughput degrades with the increment of probability of errored frame. In this case, though there is no collision, the transmitted packet is

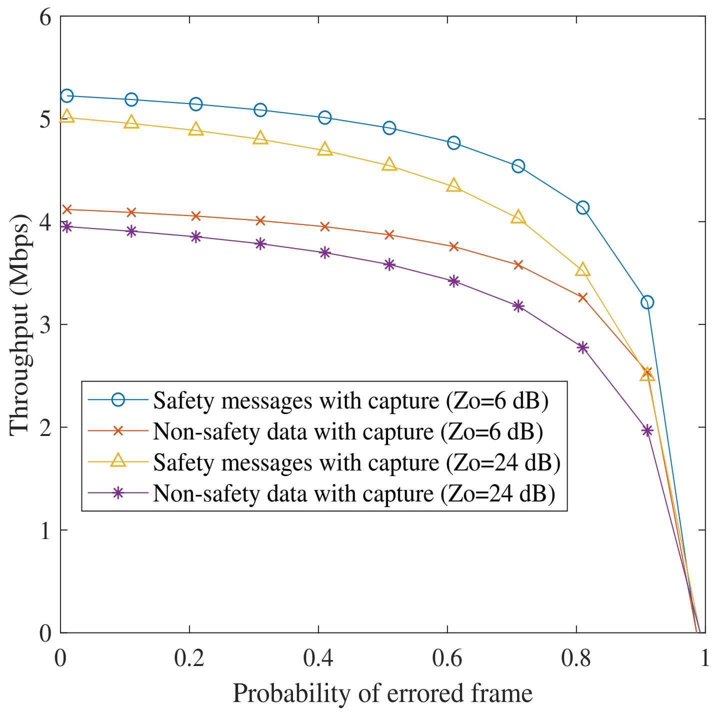

Figure 3.18 Throughput versus probability of errored frame (N=100, L=512 bytes)

lost because of decoding error under channel fading. It is also noticeable that the throughput is high when z_o is low even in the presence of channel fading because lower z_o enables higher capture effect. Capture raises the probability of successful transmission which increases throughput and throughput increases for low value of capture threshold due to presence of high capture. The throughput can be increased if the probability of frame capture can be increased and the probability of errored frame can be decreased. If there is a way to have frame captured always when there is collision, in that case the highest probability of successful transmission could be achieved.

4
Designing Cluster-Based MAC Protocol for VANETs

High node mobility is a main characteristic of VANETs. High node mobility and relative mobility among the vehicles cause dynamic topology changes and frequent link breakage which cause unstable communication. Furthermore, high overhead is required to update topology information. Cluster-based communication can improve the reliability of communication by forming a cluster with adjacent vehicles moving in the same direction. For stable and reliable cluster design, different direction moving vehicles should form a different cluster. Otherwise, forming a cluster with different direction moving vehicles will create a lot of signaling overhead for re-clustering frequently. From each cluster, a cluster head (CH) will be chosen who will coordinate communication among cluster members (CMs) inside the cluster and to the outside through roadside gateways. CH works as the access point for all kind of inter-cluster communication and intra-cluster communication. CH also facilitates cluster formation and manages cluster membership. Medium access, traffic control and quality of service (QoS) provision within a cluster are managed by the CH. Over the wide VANETs, CHs can form the dynamic virtual backbone to manage crucial tasks, for instance channel allocation and routing at higher layers. The major advantages that can be achieved by cluster-based MAC include:

1. Delay. For VANETs delay is a prime issue. Some safety messages will become stale if it is not delivered in time, it may cause an accident, e.g. when a lane change message is not sent to the nearby vehicles in time, it may cause a crash. Delay will increase significantly in high density network due to the contention based random access scheme. However, clustering can limit channel contention as well as can provide fair channel access within the cluster.

2. High Mobility. Rapid topology changes and frequent link breakage occurs due to the high relative mobility among vehicles. A cluster can be made up of neighboring vehicles in the same direction. Vehicles driving in same direction should be together to reduce relative mobility among the vehicles in the cluster. Consequently, clustering will minimize the effect of high mobility. Moreover, clustering ensures stable as well as

scalable network structures and communications. In cluster-based MAC mechanism, clustering makes VANETs into small groups which limits channel contention as well as efficiently controls the network topology.

3. Handover. Handover refers to shifting an ongoing data session of a mobile device from one base station to the next base station. Handover for VANETs is a challenging issue due to fast moving vehicles. Many cellular radio channels must be reserved if vehicles are to remain connected to roadside cellular systems to transfer to the next roadside station while moving. Furthermore, overhead would be high between the vehicles and the stations due to demanding handover, informing channels, as well as continuing interrupted traffic signaling. If there is not enough handover channels, collisions or interruptions may occur. Clustering can expedite the handover method to a great extent by congregating handover requests. Consequently, only a single handover is originated (between CH and roadside system) which increases handover success rate and reduces the number of reserved handover channels as well as signaling overhead [28].

In this chapter, a novel cluster-based MAC (CB-MAC) protocol for VANETs is proposed. The main objective of the proposed CB-MAC protocol is to enhance the reliability of communications in VANETs by mitigating impairments due to the user mobility and to improve communication quality with higher throughput and lower delay, in particular safety messages should not experience delay more than 100 ms [5–7]. The CB-MAC protocol is designed for both safety messages and non-safety data transmission. The cluster formation mechanism is defined. The procedure of joining as well as leaving the cluster is provided. Moreover, CH election process is described. The IEEE 802.11 standard supports only direct communication and is not designed for cluster-based communication. Hence, new control packets are presented and the current control packet format is changed to support cluster-based communications. For designing effective MAC protocol, the RTS/CTS mechanism is not used for sm, but the RTS/CTS mechanism is used for nsd delivery to abolish the hidden node problem. Markov chain model based analytical analysis of the proposed CB-MAC protocol is provided. Throughput, packet dropping rate (PDR), and delay expressions are obtained. Besides, overhead introduced by the CB-MAC protocol is considered. Moreover, the CB-MAC protocol is verified by numerical results. The numerical results demonstrate that the CB-MAC protocol outperforms existing schemes under the same network scenarios and improves system performance. Cluster-based MAC (CB-MAC) protocol and QoS aware cluster-based MAC (qCB-MAC) protocol are presented in Section 4.2 and Section 4.3, respectively.

4.1 CB-MAC Protocol

The finite state machine (FSM) of the CB-MAC protocol is provided in Figure 4.1. The FSM is outlined by Unified Modeling Language (UML). Each vehicle has a global positioning system (GPS) installed that provides the location and direction information of the vehicle. The cluster will be formed by grouping nearby same direction driving vehicles. A palpable example is presented in Figure 4.2.

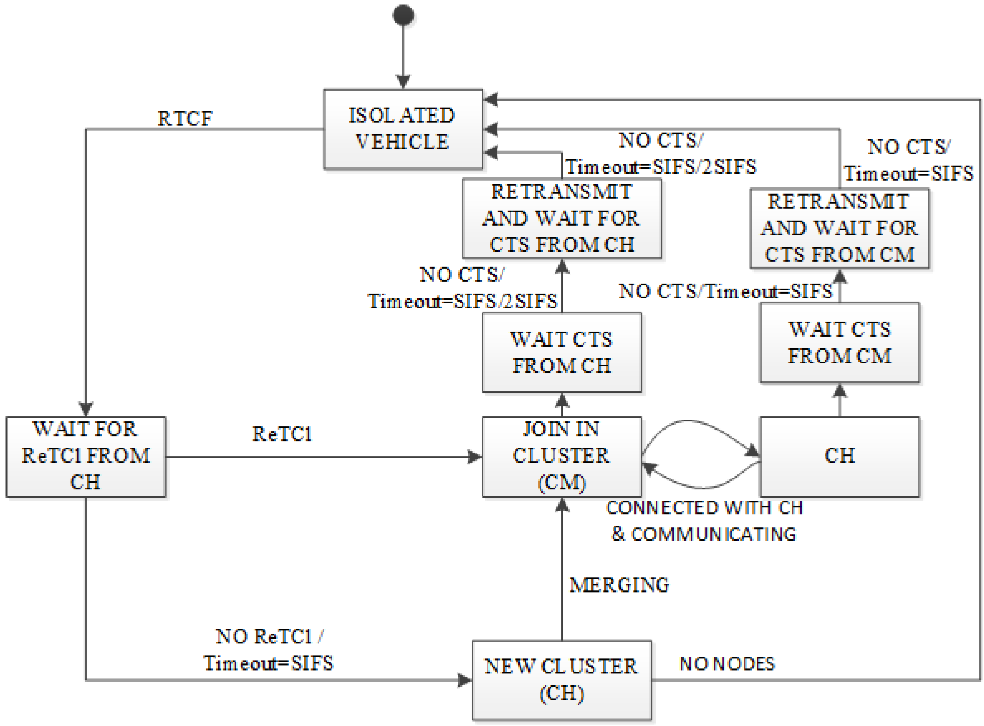

Figure 4.1 The finite state machine of CB-MAC protocol

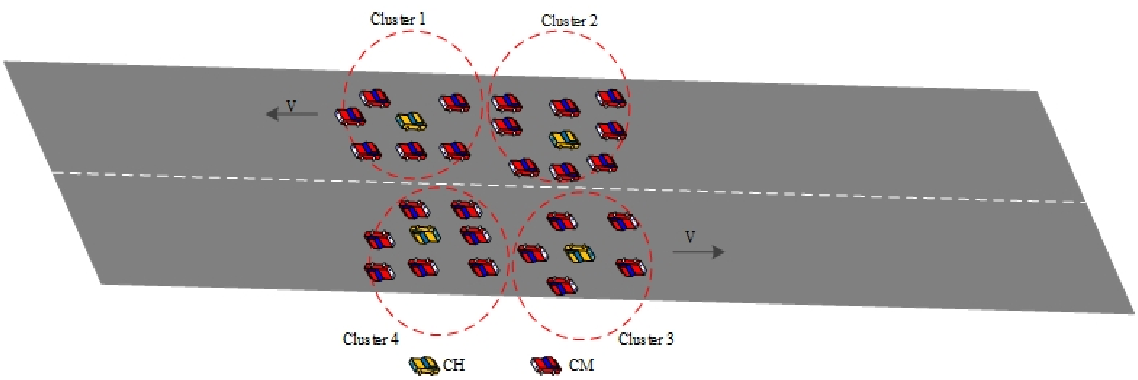

Figure 4.2 Application scenario

One vehicle will be elected as a CH and remaining other nodes are CMs. All CMs can communicate with the CH directly. The CH gathers and broadcasts messages in its cluster as well as being responsible for communication out of the cluster. The CH works as an access point for all type of communication. To support cluster-based communication, new control packets: RTCF (Request To Cluster Formation), ReTCl (Registration To Cluster), RClM (Request To Cluster Merging) are introduced in this protocol and control packets format of IEEE 802.11 are altered.

4.1.1 Formation of CB-MAC cluster

The cluster formation mechanism will be defined in this section. The operational process of CB-MAC protocol will be discussed. Newly introduced packet format and modified packet format is given in Figure 4.3.

RTS

Frame Control	Duration	RA	TA	Cl-ID	FCS

RTCF

Frame Control	Duration	TA	ClI	FCS

ReTCl

Frame Control	Duration	RA	Cl-ID	CHA	CM-ID	FCS

CTS

Frame Control	Duration	RA	Cl-ID	FCS

ACK

Frame Control	Duration	RA	FCS

RClM

Frame Control	Duration	Cl-ID	CHA	CMI	FCS

Figure 4.3 Modified control packet format

4.1.1.1 Cluster Membership

When an isolated vehicle wants to join a cluster, it will broadcast RTCF in the network. Cluster Information required (ClI) field is added in the RTCF control packet. If there exists any cluster then CH will transmit ReTCl to the isolated vehicle assigning a cluster member ID (CM-ID). ReTCl includes cluster ID (Cl-ID), Cluster Head Address (CHA) and newly assigned CM-ID. If multiple ReTCl are received by the isolated vehicle, it will join in the first cluster from which ReTCl is received first and discarded message will be sent to others. Delay is less if number of vehicle is less. Therefore, joining in the first cluster means joining in the cluster which ReTCl arrives with lower delay because of lower CMs. Then CH updates the CMs list and broadcast to all CMs. If there is no cluster, then the isolated vehicle will not receive any ReTCl and short inter frame space (SIFS) timeout will occur. The isolated vehicle will form a new cluster assigning a new cluster ID and itself will be the CH. After that new cluster information will be broadcast in the network.

4.1.1.2 CH Election

If any isolated vehicle does not receive ReTCl or SIFS interval timeout occurs after broadcasting RTCF, then the isolated vehicle will form a cluster. The vehicle will be CH itself. However, if there is any cluster and the isolated vehicle receives ReTCl, then the vehicle will join in the cluster as a CM, because there is already a cluster and a CH.

4.1.1.3 Leaving a Cluster

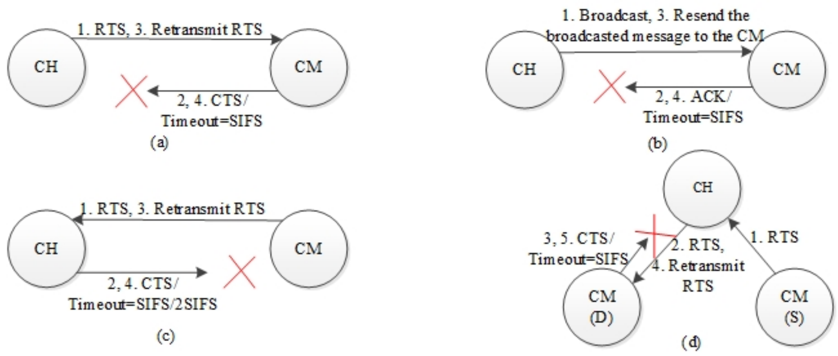

Figure 4.4 Modified cluster leaving process: (a) while data transmission from CH to CM; (b) while broadcast message transmission from CH to CMs; (c) while data transmission from CM to CH; (d) while data transmission from CM to CM

CMs list has to be realistic and dynamically updated. CMs list will be updated dynamically while a new CM joins in the cluster or leaves the cluster. Cluster leaving process can be done both by CM and CH. Cluster leaving process is presented in Figure 4.4. Cluster leaving process when CH wants to send data to CM is shown in Figure 4.4 (a). While CH sends RTS to CM for sending data, CH waits for CTS until SIFS timeout to send data. If CH does not get any CTS after SIFS timeout period, the CH will retransmit the RTS and wait for CTS or SIFS timeout. If CTS is not received within SIFS interval, CH will infer the CM is out of the transmission range of CH, and delete the CM from CM list and broadcast in the network. Cluster leaving process when CH broadcasts message to all CMs is shown in Figure 4.4 (b). In response to the broadcast message in the cluster, all CMs will send an acknowledgment (ACK) to the CH. If CH does not receive ACK from a CM upon retransmission after a failed transmission and SIFS interval timeout occurs, then CH will recognize the CM is now out of transmission range. Cluster leaving process when a CM (sender (S)) transmits data to CH as well as to another CM (destination (D)) are presented in Figure 4.4 (c) and 4.4 (d) respectively. CM (S) will wait for CTS after sending RTS from CH to communicate with CH or another CM (D). If a CM (S) sends RTS to CH will wait for SIFS interval timeout and 2SIFS interval timeout if RTS is sent to another CM (D). When a CM does not receive CTS and timeout occurs, the CM will retransmit RTS (Figure 4.4 (c)) or the CH will retransmit the RTS (Figure 4.4 (d)). Even then, if CTS is not received and a timeout occurs, the CM will leave the cluster and will broadcast RTCF to form a new cluster, because the CM already left the cluster transmission area.

4.1.1.4 Cluster Merging

If two or more CHs come in the same network coverage, they will merge. When a CH receives control messages for example CM list message from another CH, then the CH realizes that there are multiple CHs in the same network coverage. After that, the CH will broadcast RClM. Cluster member information (CMI) field is added in the RClM control packet from which the number of CMs of that cluster can be found. After hearing an RClM, other CHs will also broadcast own RClM. In cluster merging process, CH who has the most number of CMs will remain the CH. Other CHs and CMs will join in the cluster as CM. Then the CH of merged clusters updates the CMs list and broadcast to all CMs.

4.1.2 Safety Message Transmission

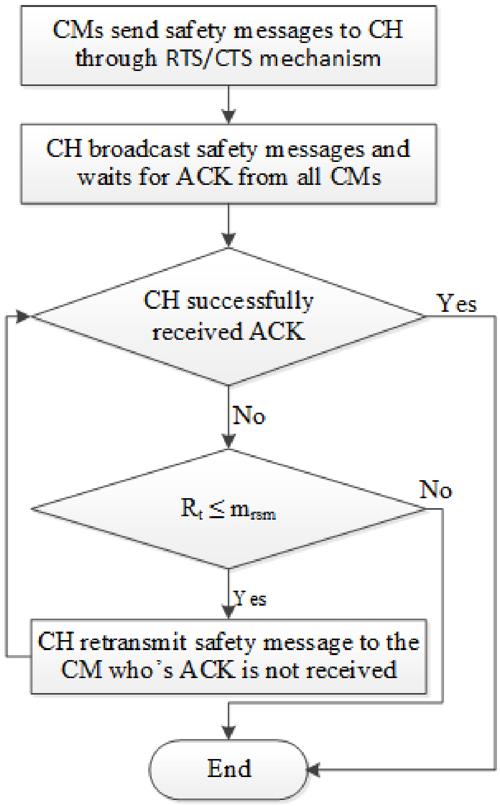

Figure 4.5 Flowchart of the proposed CB-MAC protocol for safety message

Safety related messages, for instance, emergency cautionary, accident prevention, street state, way changing support, emergency electronic brake light indication etc. are the utmost vital messages in VANETS which have strict delay requirement. CMs send safety message to the CH via RTS/CTS mechanism. Since multiple CMs may send safety messages to the CH, to reduce packet collisions due to hidden node problem RTS/CTS mechanism is used. CH broadcasts safety messages and waits for ACK from all CMs. If ACK is received from all CMs, then the broadcast is successful. Otherwise, if ACK is not received and for the failure transmission if the number of retransmission (Rt) is less than or equal to the maximum retransmission limit for safety messages (m_{rsm}), then safety messages will be transmitted to the CM who's ACK is not received. CH always broadcasts safety messages without RTS/CTS because CTS from all CMs will create collision. To ensure reliable transmission ACK is used. Figure 4.5 demonstrates the flowchart of the proposed CB-MAC protocol for safety message.

4.1.3 Non-safety Data Transmission

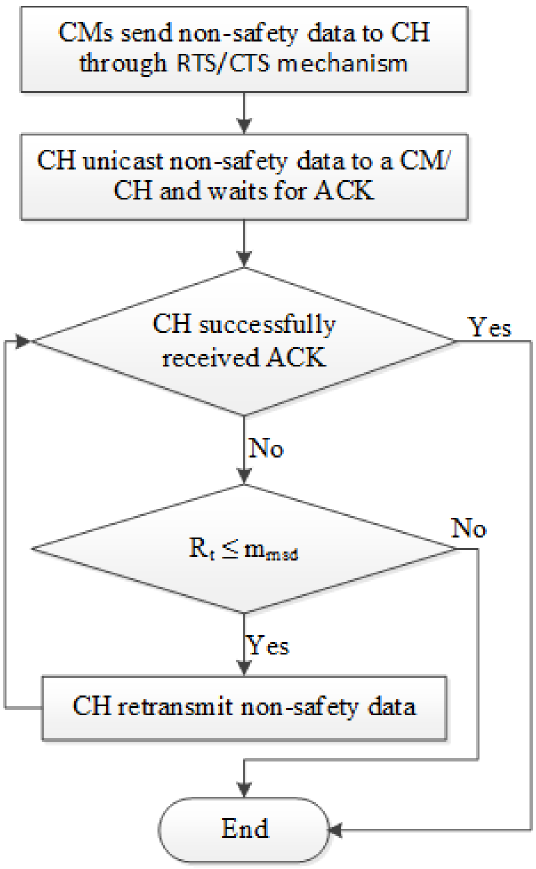

Figure 4.6 Flowchart of the proposed CB-MAC protocol for non-safety data

VANETs also support non-safety data transmission, for instance, web browsing, content distribution, map update, video download, gaming, entertainment etc. Non-safety data will be unicast to a CM or a CH from a CH or a CM. There are three types of unicast for non-safety data transmission: (a) CH to CM, (b) one CM to another CM via CH, and (c) one CH to another CH. CH unicast non-safety data to a CM directly and waits for ACK to understand successful or failure data transmission. If one CM send non-safety data to another CM; firstly, non-safety data will be sent to CH through RTS/CTS mechanism, then CH will send non-safety data to CM (destination (D)). CH will send ACK to CM (sender (S)) after getting the ACK from CM (D). If one CH transmits non-safety data to another CH, then it will be transmitted through RTS/CTS mechanism to avoid packet collisions because of hidden node problem. If ACK is not received, then the delivery is not successful. If the number of retransmission (Rt) for the failure transmission is less than or equal to the maximum retransmission limit for non-safety data (m_{rnsd}), then non-safety data will be retransmitted. Figure 4.6 demonstrates the flowchart of the proposed CB-MAC protocol for non-safety data.

4.1.4 CH and CM Handshake

Handshake between CH and CM for safety message and non-safety data is shown in Figures 4.7 and 4.8 respectively. When a CH identifies an emergency situation, it will broadcast the sm to all CMs. CMs will send ACK after receiving the safety message. For failure transmission, CH will retransmit to particular CM who did not send ACK. If a CM identifies an emergency state it will send data to CH through RTS, CTS, DATA, ACK to avoid hidden node problem. After that, CH will broadcast the safety message to all CMs and waits for ACK. If ACK is not received, CH will retransmit safety message to the CM who did not send ACK. The safety message can be retransmitted until maximum retransmission limit for safety messages.

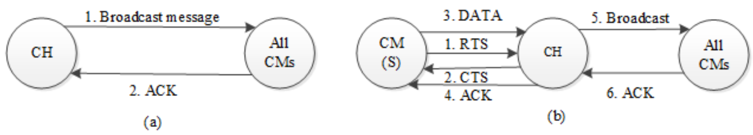

Figure 4.7 CH and CM handshake for safety messages: (a) broadcast message from CH to all CMs; (b) broadcast message from CH to all CMs upon receiving from CM

Non-safety data transmission from a CH to a CM is shown in Figure 4.8 (a). Non-safety data will be to a CM from the CH directly. After that, CH waits for ACK to detect failure transmission. Unacknowledged transmission will be retransmitted. If a CM sends data to another CM, the data will be transmitted through CH. The data exchange procedure from one CM to another CM is depicted in Figure 4.8 (b). CM send data to the CH after RTS/CTS exchange, then CH forward data to another CM (D). Then, CM (D) send ACK to CH and CH send ACK to CM (S). The data communication beyond the cluster will be done by CH too. Data transmission between clusters will

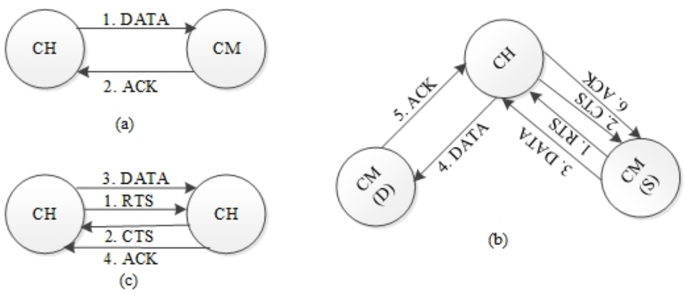

Figure 4.8 CH and CM handshake for non-safety data: (a) data transmission between CH and CM; (b) data transmission between one CM and another CM through CH; (c) data transmission between two CHs

be coordinated by CHs. Non-safety data transmission between two CHs is presented in Figure 4.8 (c). The non-safety data transmission from one CH to another CH is accomplished by RTS/CTS mechanism. The non-safety data will be retransmitted if ACK is not received until maximum retransmission limit for non-safety data.

4.1.5 Performance Analysis

A VANET with N vehicles in r_t transmission range is considered. Same VANET scenario is considered which is mentioned in Section 2.2.1 from eq. (2.1) to eq. (2.6).

Let j be the number of clusters are formed in the vehicular network by grouping neighboring vehicles which are moving in the identical direction. Average number of vehicle in a cluster can be given as

$$x = N/j. \tag{4.1}$$

There will be one CH from each cluster. Therefore, there is j number of CHs. Average number of CMs in a cluster can be written as

$$y = x - 1 = (N - j)/j. \tag{4.2}$$

P_{t-cl} is the probability that CM transmits packet in a slot, can be given as

$$P_{t-cl} = y/x = (N - j)/N. \tag{4.3}$$

P_c is the collision probability that a collision may occur for a transmitted packet. Collision will happen while one of the remaining $x - 2$ vehicles transmit packet in the same slot time. If P_{t-cl} is the packet transmission probability for each CM then P_c can be given as

$$P_c = 1 - (1 - P_{t-cl})^{x-2}. \tag{4.4}$$

P_i is the channel idle probability in any state and can be given as

$$P_i = (1 - P_{t-cl})^{x-1}. \tag{4.5}$$

P_b is the channel busy probability that minimum one vehicular node is transmitting in that slot. As $x-1$ CMs compete for the channel, therefore the P_b can be given as

$$P_b = 1 - P_i = 1 - (1 - P_{t-cl})^{x-1}. \tag{4.6}$$

P_s is the successful transmission probability which can be given as

$$P_s = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}}{P_b} = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}}{1-(1-P_{t-cl})^{x-1}}. \tag{4.7}$$

Let T_e is the expected time spent in each Markov state by a vehicular node. T_e can be given as

$$T_e = P_i T_{slot} + P_{busy} P_s T_s + P_b(1-P_s)T_c \tag{4.8}$$

where T_{slot} is the span of a slot time, T_s is the time span when a packet is successfully transmitted and Tc is the period of time when a packet is transmitted with the collision.

For the proposed CB-MAC protocol T_s and T_c for both safety messages (sm) and non-safety data (nsd) can be expressed as follows

$$T_{s-sm(CH-CM)} = T_{SIFS} + \frac{L_h + L}{R_d} + T_{ACK} + T_{delay}, \tag{4.9}$$

$$T_{s-sm(CM-CM)} = T_{DIFS} + 4T_{SIFS} + \frac{L_h + (x+1)L}{R_d} + T_{delay} + T_{RTS} + T_{CTS} + (x+1)T_{ACK}, \tag{4.10}$$

$$T_{s-nsd(CH-CM)} = T_{DIFS} + 3T_{SIFS} + \frac{L_h + L}{R_d} + T_{delay} + T_{RTS} + T_{CTS} + T_{ACK}, \tag{4.11}$$

$$T_{s-nsd(CM-CM)} = 2T_{DIFS} + 6T_{SIFS} + \frac{L_h + 2L}{R_d} + T_{delay} + 2T_{RTS} + 2T_{CTS} + 2T_{ACK}, \tag{4.12}$$

$$T_c = T_{DIFS} + T_{RTS} + T_{delay}, \tag{4.13}$$

where L_h is the length of MAC and PHY header, L is the size of the transmitted packet and R_d is the data transmission rate. T_{RTS}, T_{CTS} and T_{ACK} are the time span for RTS, CTS and ACK, respectively. $T_{dela}y$ denotes the propagation delay.

Let O be the overhead introduced by the proposed CB-MAC protocol for safety messages (sm) and non-safety data (nsd) which can be expressed as follows:

$$O_{s-sm(CM-CM)} = T_{SIFS} + \frac{xL}{R_d} + xT_{ACK} \tag{4.14}$$

$$O_{s-nsd(CM-CM)} = T_{DIFS} + 3T_{SIFS} + \frac{L}{R_d} + T_{RTS} + T_{CTS} + T_{ACK}. \tag{4.15}$$

4.1.5.1 Throughput Analysis

The S can be given for kth cluster as follows:

$$S_k = \frac{P_s P_{busy} L}{T_e} = \frac{P_s P_{busy} L}{P_i T_{slot} + P_{busy} P_s T_s + P_{busy}(1-P_s)T_c}. \tag{4.16}$$

Using Eq. (4.5) – Eq. (4.7), the S for kth cluster can be derived as

$$S_{ksm} = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}L}{(1-P_{t-cl})^{x-1}T_{slot} + (x-1)P_{t-cl}(1-P_{t-cl})^{x-2}T_{s-sm} + AT_c}, \tag{4.17}$$

$$S_{knsd} = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}L}{(1-P_{t-cl})^{x-1}T_{slot} + (x-1)P_{t-cl}(1-P_{t-cl})^{x-2}T_{s-nsd} + AT_c}. \tag{4.18}$$

where $A = \left[\left(1-(1-P_{t-cl})^{x-1}\right) - \left((x-1)P_{t-cl}(1-P_{t-cl})^{x-2}\right)\right]$. Thus, S can be written as

$$S = \sum_{k=1}^{j} S_k. \tag{4.19}$$

4.1.5.2 Packet Dropping Rate Analysis

Let PDR_{sm} and PDR_{nsd} be the packet dropping rate (PDR) for safety messages (sm) and non-safety data (nsd) respectively. A packet will be dropped after the maximum retransmits limit. PDR_{sm} and PDR_{nsd} can be expressed as follows:

$$PDR_{sm} = (1-P_s)^{m_{rsm}}, \tag{4.20}$$

$$PDR_{nsd} = (1-P_s)^{m_{rnsd}} \tag{4.21}$$

where m_{rsm} and m_{rnsd} are the maximum retransmission limit for safety messages and non-safety data respectively.

4.1.5.3 Delay Analysis

Let $E[D]$ be the mean packet delay that is the mean delay of a successful packet transmission which can be given as

$$E[D] = E[T_{interval}] - \frac{P_{fdrop}}{1 - P_{fdrop}} E[T_{drop}] \tag{4.22}$$

where $E[T_{interval}]$ is the mean packet interval time at one receiver between two successful reception of packets, P_{fdrop} is the probability that a packet is dropped lastly, and $E[T_{drop}]$ is the mean time to drop a packet.

$E[T_{interval}]$ can be calculated as

$$E[T_{interval}] = NT_e. \tag{4.23}$$

$E[T_{drop}]$ can also be calculated as

$$E[T_{drop}] = E[X_{drop}]T_e \tag{4.24}$$

where $E[X_{drop}]$ denotes the mean slot time for the dropping packet which is

$$E[X_{drop-sm}] = \frac{2}{1 + CW + m_{rsm}CW/2}, \tag{4.25}$$

$$E[X_{drop-nsd}] = \frac{2}{1 + CW + m_{rnsd}CW/2}. \tag{4.26}$$

where CW is the contention window. Thus, using equations from (4.22) to (4.26) the mean packet delay can be given as

$$E[D_{sm}] = T_e \left(N - \frac{P_{drop}}{1 - P_{drop}} \times \frac{2}{1 + CW + m_{rsm}CW/2} \right). \tag{4.27}$$

$$E[D_{nsd}] = T_e \left(N - \frac{P_{drop}}{1 - P_{drop}} \times \frac{2}{1 + CW + m_{rnsd}CW/2} \right). \tag{4.28}$$

4.1.6 Numerical Results

The performance of the CB-MAC protocol is evaluated in this section. The numerical analysis is conducted in MATLAB. A VANET of arbitrarily distributed vehicles running through a two lane road is considered where each road width is 5 m. We assume that all the vehicle's velocity in a cluster is nearly the same which is 100 km/h and the transmission range is 500 m. We considered the ideal channel condition.

The comparison between the proposed CB-MAC protocol and traditional MAC model which is based on the IEEE 802.11 DCF is provided. Moreover, a quantitative comparison with existing cluster-based schemes is presented. Table 4.1 provides the value of parameters utilized in the numerical analysis.

Table 4.1 Value of parameters utilized in numerical analysis

Parameters	**Value**
$T_{slot}, T_{delay}, T_{SIFS}, T_{DIFS}$ μs	20, 1, 10, 50
RTS, CTS, ACK (bytes)	27, 21, 14
RTCF, ReTCI (bytes)	26, 28
L_h, L (bytes)	50, 512
R_c, R_d, λ (Mbps)	1, 11, 0.5
$m_r, m_{rsm}, m_{rnsd}, CW$	7, 2, 7, 64
β (m)	10
v (km/h)	100
D_T (veh/m)	0.5
N (m)	50
r_t (m)	500

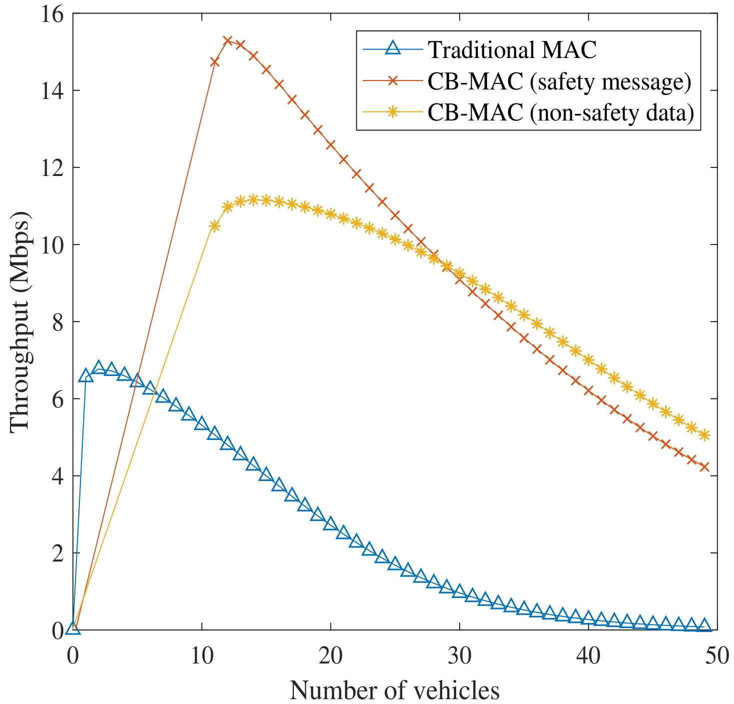

Figure 4.9 Throughput against number of vehicles

Figures 4.9 and 4.10 show the throughput against a number of vehicles and number of vehicles under the different size of cluster respectively. Cluster size is 5 in Figure 4.9. It is obvious that there is a remarkable improvement of throughput in the CB-MAC protocol for both sm and nsd. While the number of vehicles goes up

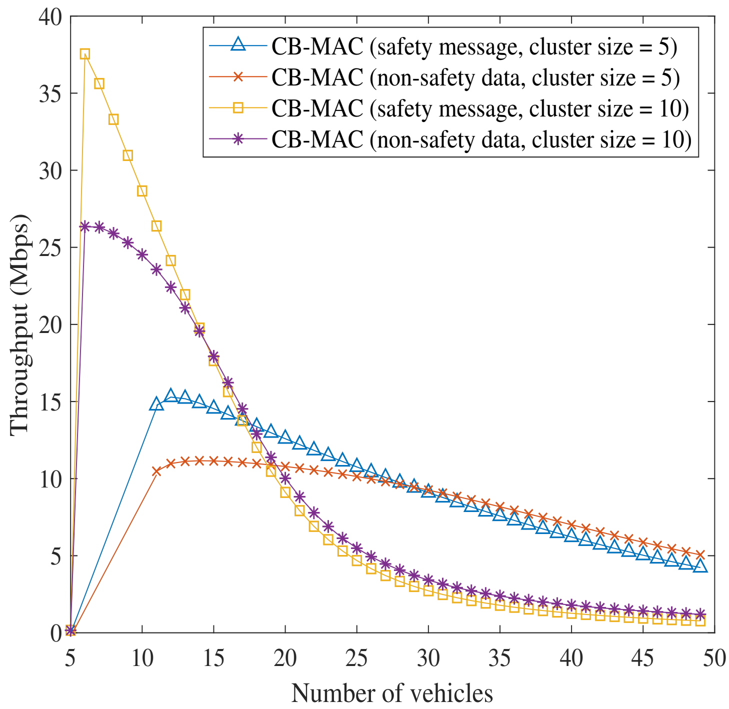

Figure 4.10 Throughput against number of vehicles under different size of cluster

within a certain range, the throughput increases because it would not originate many collisions. However, when the number of vehicular nodes further go up, additional packets will contend for transmission which causes more collision and degrades throughput. Moreover, Figure 4.10 demonstrates that cluster size effects the throughput for 50 vehicles with cluster size 5 and 10, here vehicle number denotes cluster size. As channel contention, packet loss, collision probability hinges on the number of vehicles in the cluster, system throughput also hinges on cluster size. If cluster size becomes large, there will be high number of packet collisions between large numbers of vehicles which will reduce system performance dramatically. Furthermore, a large geographical area may cause high transmission failures. In contrast, a small cluster could not be able to utilize the available radio resources due to an inadequate number of vehicles in the cluster and low traffic demand generated in the cluster. Since throughput is highest for certain number of vehicular nodes, there is an optimum cluster size which can achieve the highest throughput. It is noticeable that the throughput of safety messages is higher than the non-safety data because CH immediately broadcasts the emergency message to all CMs through the control channel (CCH) without channel contention and there is no need to transmit RTS, as a result, waiting for CTS is not required. However, non-safety data is intended for a CM, not for all CMs. Therefore, non-safety data will not be broadcast. Non-safety data will be transmitted to the desired CM after RTS and CTS transmission to avoid hidden node problem as well as to ensure that the CM is still in the cluster.

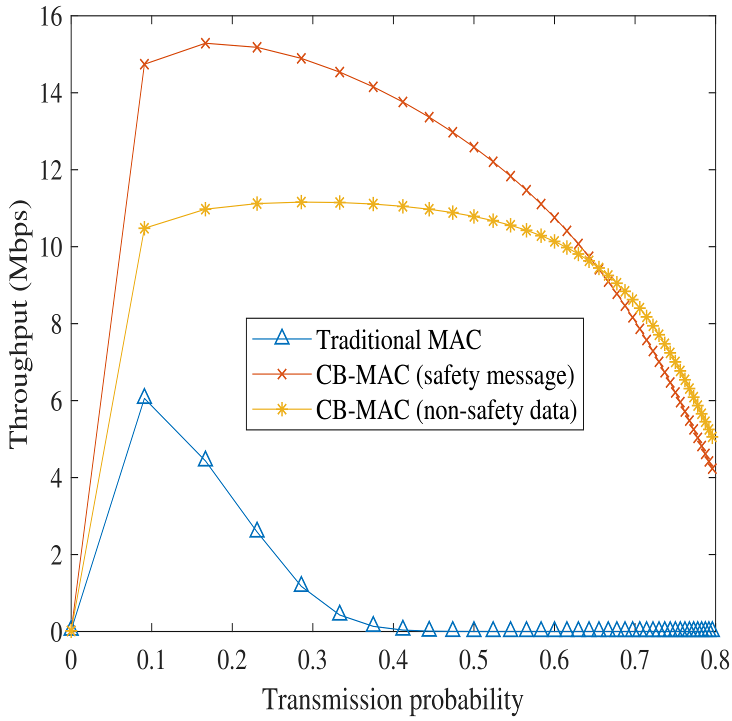

Figure 4.11 Throughput against transmission probability

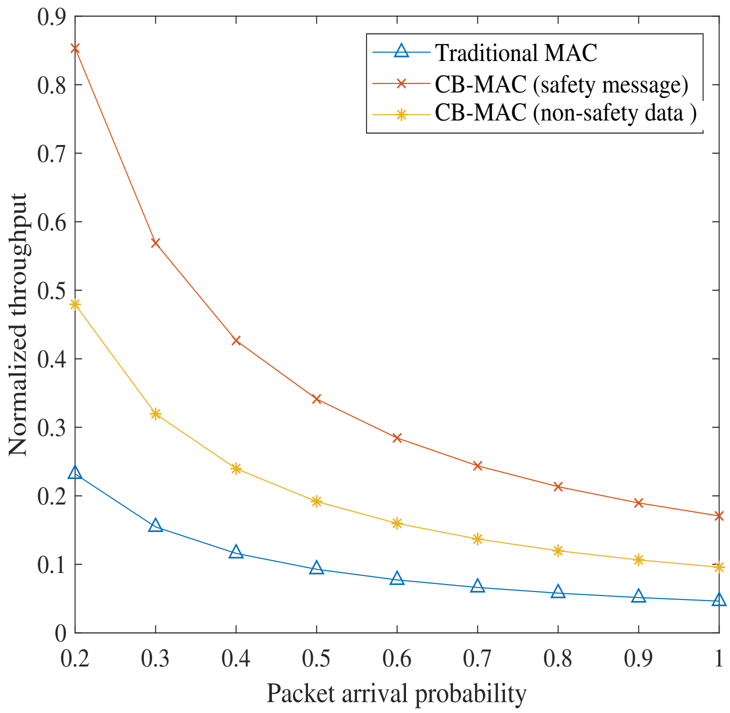

Figure 4.12 Normalized throughput against packet arrival probability

Figure 4.11 shows the throughput against transmission probability. The throughput increases with the increase of transmission probability within a certain range because this would not originate many collisions. Nevertheless, if the transmission probability

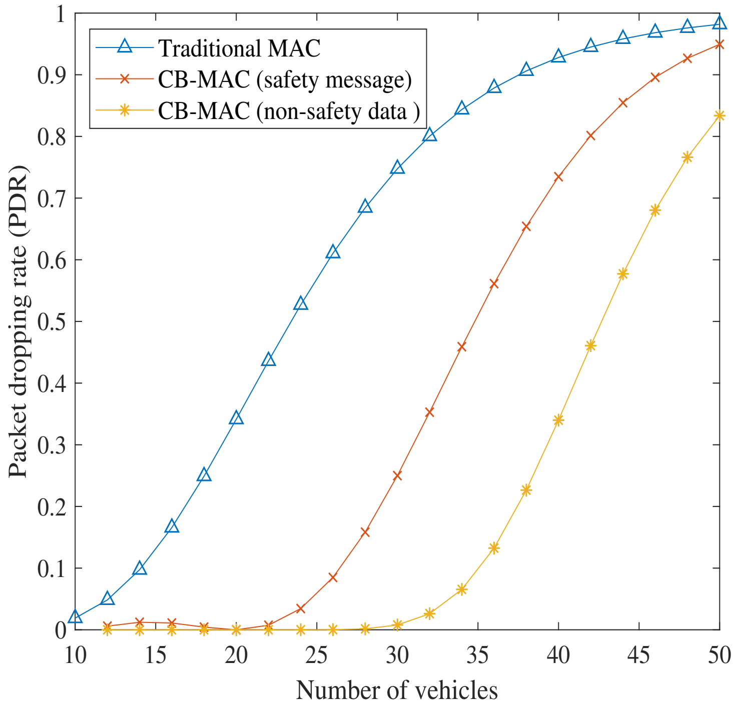

Figure 4.13 PDR against number of vehicles

further goes up, there are more collisions and throughput is reduced. Figure 4.12 presents the normalized throughput versus packet arrival probability. The data packets arrive following a Poisson process with mean 0.5 Mbps. The system throughput decreases when the packet arrival probability increases. When the packet arrival rate is high, the probability of packet collisions is high. When there are more vehicles in the network, there is more probability for packet arrival. In Figures 4.9 to Figures 4.12, it can be seen that sm have higher throughput than nsd because sm are broadcast without any other control message transmission and nsd is transmitted after RTS and CTS transmission.

Figure 4.13 exhibits the PDR against number of vehicles. For the same retransmission limit, the PDR of non-safety data is significantly less than the traditional MAC. Though the PDR of safety messages is less than the traditional MAC, it is more than non-safety data because retransmission limit is less for safety messages and safety messages are broadcast immediately without RTS/CTS transmission. Even though safety messages PDR is higher than non-safety data, safety messages can be retransmitted until all ACKs are received.

Figure 4.14 depicts average packet delay versus number of vehicles. Average packet delay is increasing dramatically while the number of vehicles is increasing. PDR and delay are increasing with increase of the number of vehicles because collision

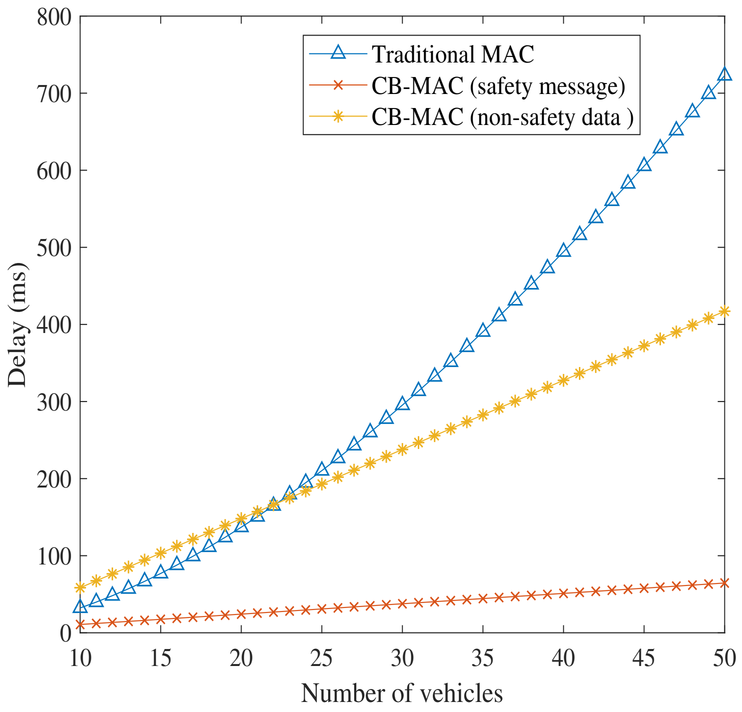

Figure 4.14 Delay against number of vehicles

probability is increasing with increase of the number of vehicles. It is noticeable that for non-safety data transmission, the delay is slightly higher than traditional MAC for lower traffic but when traffic is increasing the delay become less than traditional MAC. It is also observable that the average delay of sm is lower than nsd. Since no other control packets are broadcast before sm, sm are broadcast immediately after getting the channel. On the other hand, nsd is transmitted after transmission of RTS and CTS. Therefore, there is an extra transmission of RTS and CTS, and there is contention for these transmissions which increases the average delay for nsd. However, delay for safety message transmission is always less than traditional MAC and CB-MAC protocol fulfills the requirement of 100 ms latency for sm.

Under the same network scenario in existing cluster-based schemes, maximum throughput achieved against number of vehicles is about 1.1 Mbps, 1.3 Mbps, and 11 Mbps in [39, 43], and [28] respectively. On the other side, in CB-MAC protocol maximum throughput is about 15 Mbps. Besides, maximum throughput achieved against transmission probability is about 800 kbps in [39] and when transmission probability is more than 0.4 the throughput is negligible. Alternatively, CB-MAC protocol improves throughput against transmission probability significantly. In [40], the average delay for safety message is 151 ms which is more than the constraint of latency of safety messages. In [43], the average delay is also higher than the constraint of latency. On the other hand, CB-MAC protocol always ensures the constraint of latency of prime important safety messages. Finally, it is obvious that the proposed CB-MAC protocol not only achieves high throughput but also satisfies the 100 ms delay constraint for safety messages.

4.2 QoS aware CB-MAC protocol

A QoS aware cluster-based MAC (qCB-MAC) protocol for VANETs is designed. Channel access mechanism is based on the IEEE 802.11 EDCA mechanism for different access categories (ACs) to ensure desired QoS at the MAC layer.

4.2.1 Performance Analysis

For the qCB-MAC protocol T_s for both safety messages (sm) and non-safety data (nsd) can be expressed as follows

$$T_{s-sm(CH-CM)} = T_{SIFS} + T_{AIFS}[AC] + \frac{L_h + L}{R_d} + T_{ACK} + T_{delay}, \tag{4.29}$$

$$T_{s-sm(CM-CM)} = T_{AIFS}[AC] + 4T_{SIFS} + \frac{L_h + (x+1)L}{R_d} + T_{delay} + T_{RTS} + T_{CTS} + (x+1)T_{ACK}, \tag{4.30}$$

$$T_{s-nsd(CH-CM)} = T_{AIFS}[AC] + 3T_{SIFS} + \frac{L_h + L}{R_d} + T_{delay} + T_{RTS} + T_{CTS} + T_{ACK}, \tag{4.31}$$

$$T_{s-nsd(CM-CM)} = 2T_{AIFS}[AC] + 6T_{SIFS} + \frac{L_h + 2L}{R_d} + T_{delay} + 2T_{RTS} + 2T_{CTS} + 2T_{ACK}, \tag{4.32}$$

$$T_c = T_{AIFS}[AC] + T_{RTS} + T_{delay}. \tag{4.33}$$

O presents the overhead introduced by the proposed qCB-MAC protocol for safety messages (sm) and non-safety data (nsd) which can be expressed as follows:

$$O_{s-sm(CM-CM)} = T_{SIFS} + \frac{xL}{R_d} + xT_{ACK}, \tag{4.34}$$

$$O_{s-nsd(CM-CM)} = T_{AIFS}[AC] + 3T_{SIFS} + \frac{L}{R_d} + T_{RTS} + T_{CTS} + T_{ACK}. \tag{4.35}$$

Table 4.2 Value of parameter utilized in numerical analysis

Parameter	Value	Parameter	Value
$CW_{min}[0]$	3	$CW_{min}[2]$	7
$CW_{max}[0]$	7	$CW_{max}[2]$	1023
$CW_{min}[1]$	3	$CW_{min}[3]$	15
$CW_{max}[1]$	15	$CW_{max}[3]$	1023
$AIFSN[0]$	2	$AIFSN[2]$	6
$AIFSN[1]$	3	$AIFSN[3]$	9
T_{slot}, T_{delay} μs	20, 1	T_{SIFS}	10
L_h, L (bytes)	50, 512	R_c, R_d	1, 11
RTS, CTS, ACK (bytes)	20, 14, 14	v (km/h)	100
D_T (veh/km/lane)	120	r_t (m)	500

The normalized throughput can be computed for kth cluster from eq. (4.16) as follows:

$$S_k = \frac{P_s P_{busy} L}{P_i T_{slot} + P_{busy} P_s T_s + P_{busy}(1-P_s)T_c}. \tag{4.36}$$

From which

$$S_k = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}L}{(1-P_{t-cl})^{x-1}T_{slot} + (x-1)P_{t-cl}(1-P_{t-cl})^{x-2}T_s + AT_c}. \tag{4.37}$$

where $A = \left[\left(1-(1-P_{t-cl})^{x-1}\right) - \left((x-1)P_{t-cl}(1-P_{t-cl})^{x-2}\right)\right]$. Thus, the normalized system throughput S can be obtained from eq. (4.19).

4.2.2 Numerical Results

The performance of the qCB-MAC protocol is assessed in this section. The numerical results are obtained by using MATLAB. A vehicular network of 30 arbitrarily distributed vehicles running through a two-lane road with width 5 m each is modeled. The transmission range is 500 m. We assume that all the vehicle's velocity in a cluster is nearly same and the velocity is 100 km/h. The value of parameters utilized in this work is given in Table 4.2.

Figures 4.15 and 4.16 present throughput against number of vehicles and transmission probability respectively. Throughput goes up with the increase of number of vehicles until certain range. Since low number of vehicles results in low transmission probability which would not cause many collisions. Nevertheless, throughput starts to decrease with additional number of vehicles. Since additional number of vehicles causes additional transmission probability which may cause more collisions. Figures 4.15 and 4.16 also show a comparison between proposed MAC protocol and traditional MAC protocol which is based on IEEE 802.11. The proposed QoS aware cluster-based

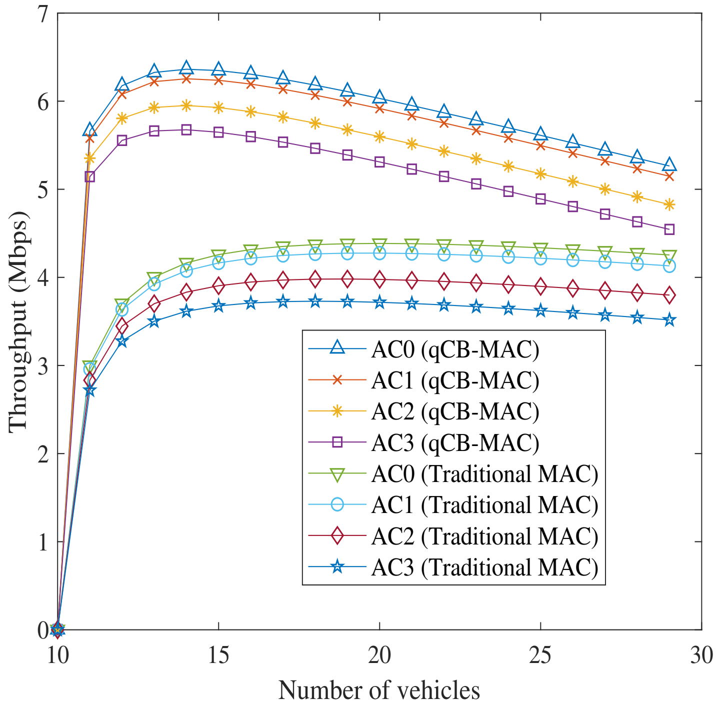

Figure 4.15 Throughput against number of vehicles

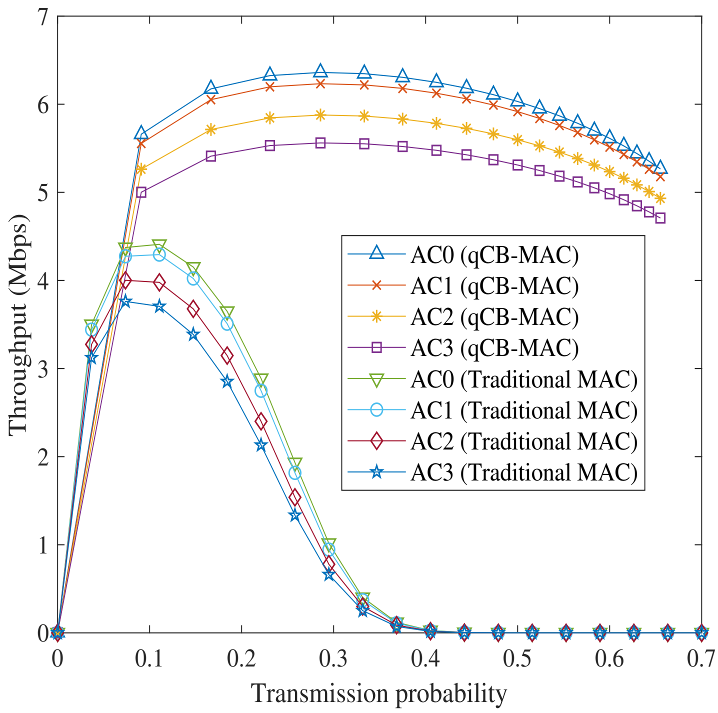

Figure 4.16 Throughput against transmission probability

MAC protocol shows a noticeable improvement for all ACs.

Figures 4.17 and 4.18 show throughput against number of clusters as well as average

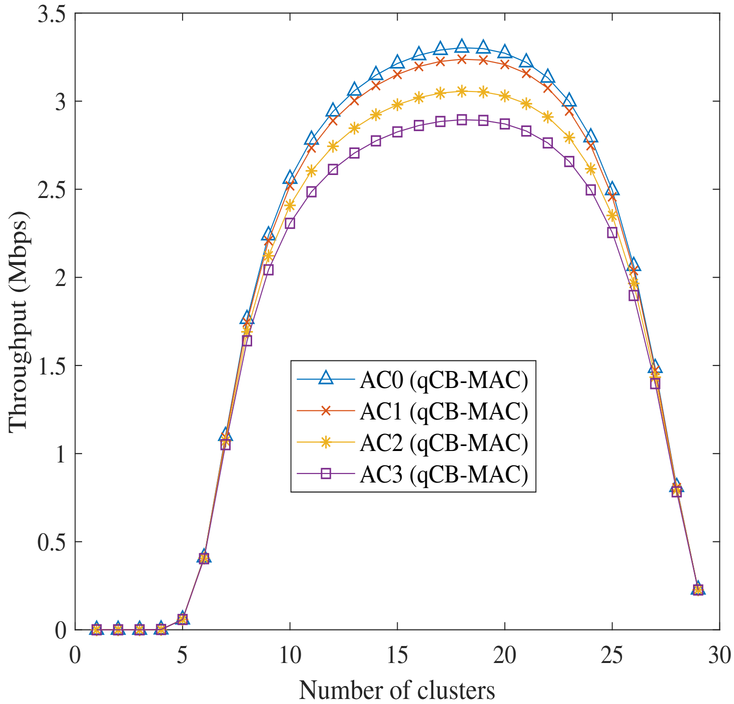

Figure 4.17 Throughput versus number of clusters

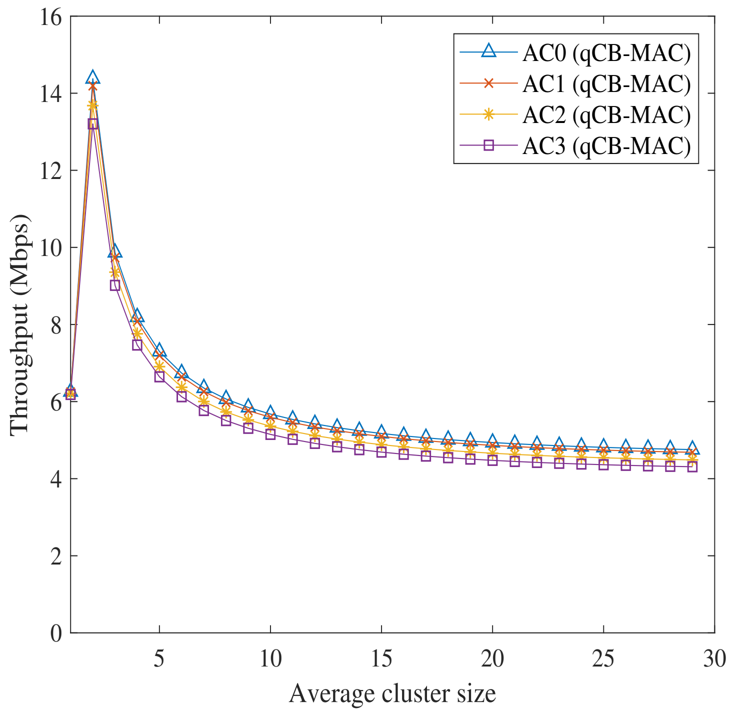

Figure 4.18 Throughput versus average cluster size

cluster size respectively. If cluster size is very small, throughput will become low. Since a small cluster is not able to utilize the available radio resources due to inadequate number of vehicles in the cluster and low traffic demand generated in the cluster.

Besides, if cluster size is very large, throughput will become low too because the packet collisions probability will be increased. For this reason, throughput is increasing with the increase of average cluster size until certain range, then throughput begins to decrease. Number of cluster being small means high number of vehicles in a cluster and number of cluster being high means low number of vehicles in a cluster. Therefore, throughput is increasing with number of cluster increasing until certain range, then throughput begins to decrease.

Moreover, it is noticeable that the AC0 attains the highest throughput among other ACs due to IEEE 802.11 EDCA parameters value. AC0 contends for transmission less time than other ACs. Throughput is decreasing from AC0 to AC3. Highest throughput belongs to AC0, then AC1, then AC2 and then AC3. The AC3 provides the lowest throughput due to long contention for transmission. Contention for the channel is done with own EDCA parameters of each AC queue. The qCB-MAC protocol improves the system throughput and ensures desired QoS.

From Figure 4.15 to Figure 4.18, it is comprehended that throughput of AC0 is higher than AC1, AC1 is higher than AC2, and AC2 is higher than AC3, and in the case of delay AC0 is lower than AC1, AC1 is lower than AC2, and AC2 is lower than AC3. The ACO has highest throughput but lowest delay and AC3 has lowest throughput but highest delay. For throughput, AC0>AC1>AC2>AC3 and for delay, AC0<AC1<AC2<AC3. The backoff process makes it possible. Since T_{AIFS} is different due to different AIFSN value, packets of different ACs have different T_{AIFS}, different ACs have different backoff. AIFSN value of ACO is lowest and AC3 is highest. For AIFSN value, AC0<AC1<AC2<AC3. Not only AIFSN value but also CW_{min} and CW_{max} influence backoff process. The lowest CWmin and CWmax has AC0 and highest CW_{min} and CW_{max} has AC3. Therefore, due to T_{AIFS}, CW_{min} and CW_{max}, packets in AC0 is transmitted first, then AC1, then AC2, then AC3 which results in highest throughput in AC0 and lowest delay in AC0, and so on.

5
Designing Reliable and Efficient Cooperative MAC Protocol for VANETs

There is no guarantee of successful transmission of prime significant safety messages in the IEEE 802.11p. Non-safety data needs huge bandwidth and good channel condition for fast transmission. Moreover, communications become unstable and topology changes promptly with frequent link breakage due to high node mobility as well as relative mobility among vehicles in VANETs which cause collision and packet loss. On the other hand, cooperative communication can increase the communication link reliability by mitigating wireless channel impairments caused by mobility in VANETs. Cooperative communication [47] improves transmission performance with the assistance of neighboring nodes. A helper node is a node among the neighboring nodes which relays packets to the receiver thanks to having a good channel condition to both the sender and receiver nodes. Due to the transmission nature of wireless communication, nearby stations can listen to the broadcast of a packet from the sender to the receiver. The overheard packet experiencing a bad channel state to the receiver can be relayed by a helper or helpers. Cooperative transmission can enhance the throughput of the whole network because of the reliability of a packet delivery with the help of helper.

In this chapter, a novel reliable and efficient cooperative MAC protocol is proposed for VANETs, referred to as RECV-MAC. The main objective of the proposed RECV-MAC protocol is to enhance the reliability of communications in VANETs by mitigating impairments due to user mobility and to improve communication quality with higher throughput and lower delay, in particular, safety messages should not experience delay more than 100 ms as stated in [5–7, 48]. Since a random access mechanism is the most suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. CSMA/CA which is used by the IEEE 802.11p. Therefore, the proposed RECV-MAC protocol is compatible with the IEEE 802.11p. New control messages are introduced to transmit safety messages and non-safety data such as Negative Acknowledgment (NACK), Keen To Help (KTH), Selected Helper Message (SHM), Willing To Involve in the offered service (WTI), Cooperative WAVE Service Advertisement (CWSA) etc. As cooperation initiates complexity and signaling overhead, cooperation all the time may not be beneficial or even needed. Cooperation becomes superfluous when cooperation gain is negligible compared to cost. Therefore, a scheme is required to decide whether a packet should be transmitted directly or cooperatively. An algorithm is suggested to determine an appropriate transmission mode. The cooperation gain depends on the helper and for that optimal helper selection procedure is also provided. Overhead introduced by cooperative communication and vehicle mobility are considered. Markov Chain model based analytical analysis of the RECV-MAC protocol is presented. Finally, the RECV-MAC protocol is evaluated by numerical studies. Numerical results show that the RECV-MAC protocol enhances the performance and achieves objectives. To the best of our knowledge, this proposed RECV-MAC protocol for VANETs is the first work on cooperation based transmission which is designed both for sm and nsd transmission that achieves the stated objectives. RECV-MAC protocol and QoS aware RECV-MAC (qRECV-MAC) protocol are presented in Section 5.2 and Section 5.3, respectively.

5.1 RECV-MAC Protocol

The proposed RECV-MAC protocol is discussed in this section. To support cooperative communication new control messages are introduced. NACK and KTH are introduced to exchange safety messages. To exchange non-safety data WTI and CWSA are introduced. SHM will be sent to the optimal helper after selecting the optimal helper. The internal finite state machine (FSM) of the RECV-MAC protocol is presented in Figure 5.1. The FSM is outlined by Unified Modeling Language (UML). For normal packet processing, 10 internal states and 15 external events are stated in the FSM. The timer value will be fixed by following the duration of the packet header for abnormal case processing. The FSM shall be reset to the “IDLE” state when timeout occurs.

The transmission of safety messages is not acknowledged in IEEE 802.11p. Therefore, unsuccessful transmission of high priority safety messages either due to collision with other packets or channel deficiencies cannot be identified. Hence, safety messages are very important, and NACK is introduced in the RECV-MAC protocol. Packets which are negatively acknowledged will be treated as failed transmissions. These packets will be sent through cooperative communication to ensure successful transmission and improve the reliability of transmission.

Non-safety data transmission consumes a large amount of bandwidth. If the main channel from the sender to the receiver is unreliable, yet other neighboring nodes have

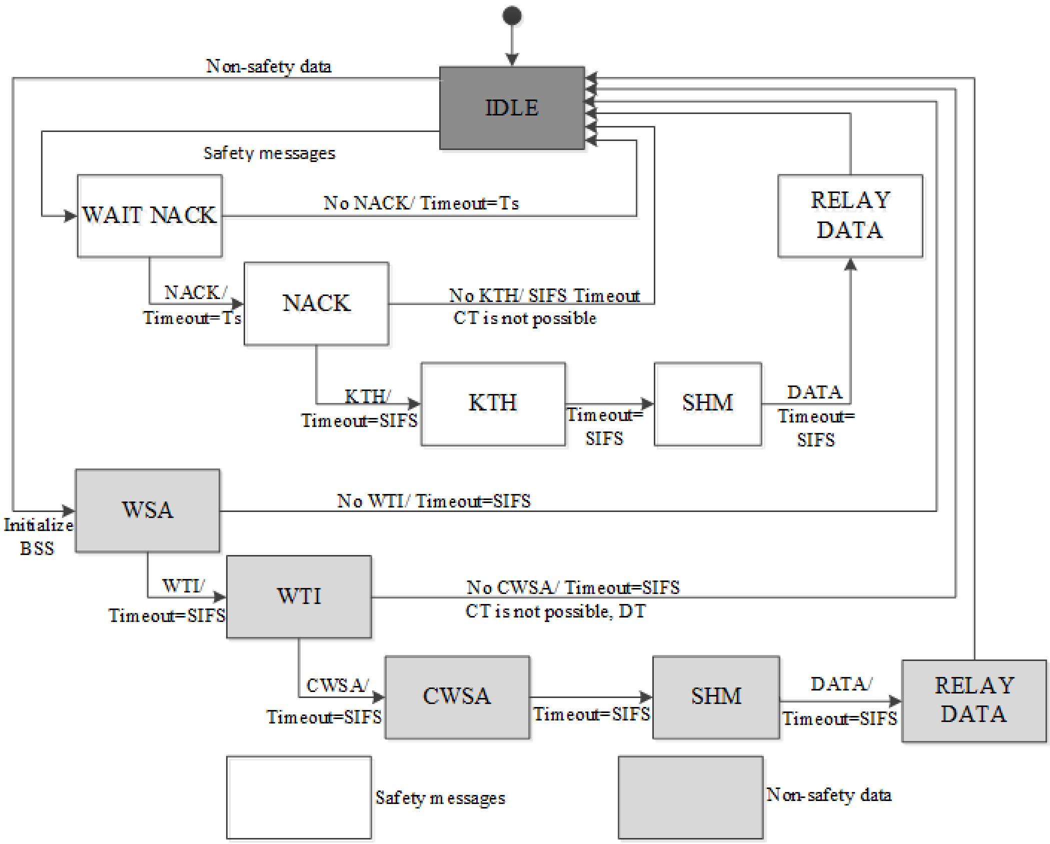

Figure 5.1 FSM of RECV-MAC protocol

a good channel state to both the sender and the receiver; then neighboring nodes can relay a packet to the receiver. Therefore, the transmission rate of non-safety data will be improved.

5.1.1 Delivery of Safety Message

Safety messages will be broadcast through CCH. To ensure a reliable broadcast service, the sender should recognize the packet is successfully transmitted to the receiver or not. After safety messages are broadcast in the network, sender S will wait for NACK from any node or timeout of successful transmission time Ts. If S receives NACK, then there is a failed transmission to a node. Otherwise, if S does not receive NACK or Ts timeout occurs, then this message broadcast is successful. A node can overhear the packet transmission from sender to other nodes [56–74]. If the node hears the message broadcast but it does not receive the message within short interframe space (SIFS) time interval, then the node will broadcast NACK for that broadcast message. The NACK includes a unique NACK ID, receiver address (RA), sender address (SA), SINR etc. After receiving the NACK, neighboring nodes which have better transmission rate, SINR, and good channel condition will send KTH to S. KTH includes NACK ID, packet ID, helper address (HA), helper SINR (H-SINR), SA, RA etc. If S does not

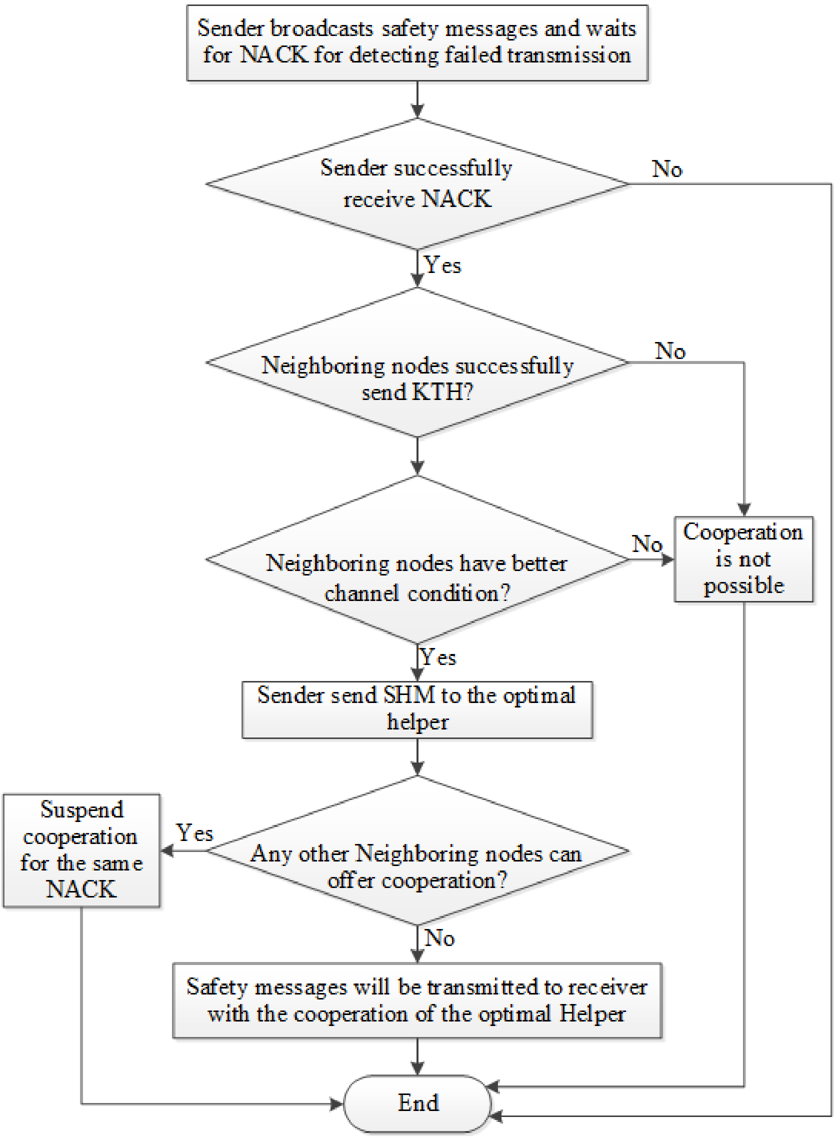

Figure 5.2 Flowchart of the RECV-MAC protocol for safety messages

receive NACK from R, S can still detect failed transmission by receiving KTH. S will choose the optimal helper among neighboring nodes which have sent KTH. If there is no KTH or SIFS timeout occurs, then cooperation is not possible. After getting KTH, the node which has optimal SINR, will be chosen by S as the optimal helper. S will send SHM to the optimal helper. SHM contains NACK ID, SA, RA, optimal helper address (OHA) etc. After hearing SHM, other nodes which can offer cooperation will suspend cooperation for the same NACK. Since safety messages are broadcast, the optimal helper has the safety message which will be relayed to the receiver node. If multiple failed transmission occurred or one NACK received with some delay, the cooperation mechanism will be completed in the same way. The cooperation will be generated by sending KTH from neighboring nodes to S. Since optimal helper is chosen based on SINR, the optimal helper can be different for different NACK. Each optimal helper will send the safety message to the particular receiver. The reliability of packet delivery is increased by cooperation of helper and packet can be delivered out of network coverage of S. All the messages will be transported through CCH. Figure 5.2 demonstrates the flowchart of the RECV-MAC protocol for safety messages.

5.1.2 Delivery of Non-Safety Data

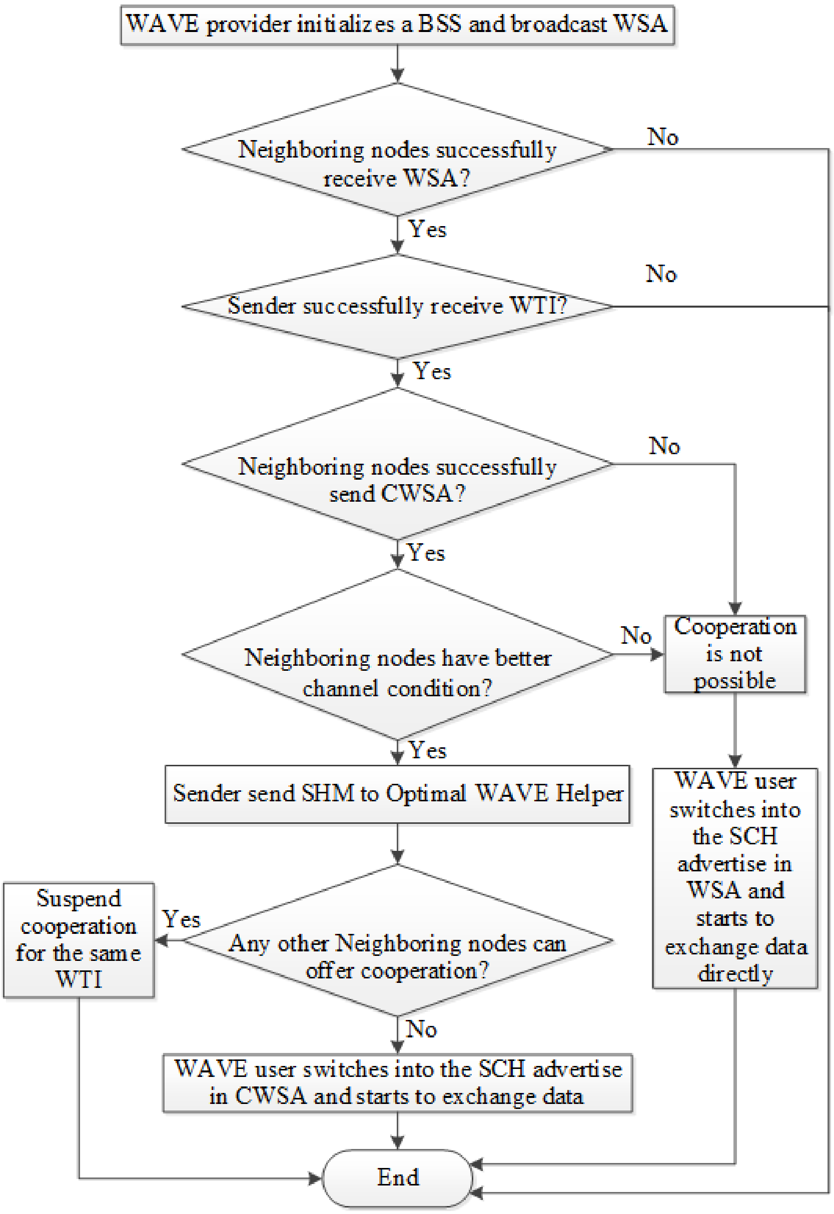

Figure 5.3 Flowchart of the RECV-MAC protocol for non-safety data

A WAVE provider (S) is a road-side unit or a vehicular node transmitting non-safety data. To provide a non-safety service, S initializes a Basic Service Set (BSS). Each S announces its existence and offers services by periodically broadcasting WAVE Service Advertisement (WSA) during CCH interval. To join the advertised BSS, WSAs enclose the necessary particulars about the offered services and the network parameters, like WSA ID, BSS ID, the Provider Service Identifier (PSID), its EDCA parameter sets, its

SCH, provider SINR, IP configuration parameters etc. WAVE user (R) is a node which is intended to involve in the offered services by S. R will send WTI which contains the WSA ID, WTI ID, WAVE provider address (SA), WAVE user address (RA), SINR etc.

If overheard neighboring nodes (H) have better channel condition and better SINR, H will send CWSA to S during CCH interval. CWSA contains all information about WSA including WTI ID, WAVE helper address (HA), SINR and channel information. After getting CWSA, S will choose the node which has optimal SINR as an optimal WAVE helper. S will send SHM to the optimal WAVE helper (H). After hearing SHM, other nodes which can offer cooperation will suspend cooperation for the same WTI. The optimal WAVE helper will join in the BSS and S transfer the non-safety data to R through the optimal H. The optimal H switches into the SCH advertised in the WSA and R switches into the SCH advertised in the CWSA and exchange data. Otherwise, if no SHM found i.e. WAVE helper is not available, then R switches into the SCH advertised in the WSA and initiates to exchange data with the S directly. Figure 5.3 presents the flowchart of the RECV-MAC protocol for non-safety data.

5.1.3 Transmission Mode Selection

As cooperation introduces complexity and signaling overhead, cooperation in the network may not be advantageous or even essential all the time or cases. Unnecessary cooperation should be avoided for optimal MAC protocol design. Two transmission modes are suggested in the RECV-MAC protocol for performance optimization which are direct transmission (DT) mode and cooperative transmission (CT) mode. The algorithm to achieve the appropriate data transmission mode for safety messages is provided in Table 5.1.

In this model, the VANET consists of N vehicles. Let U be the set of vehicles in the same network, S the sender, R the receiver, Uh the set of helper H_i, U_{NACK} the set of negative acknowledgment R_{NACK} where negative acknowledgment is sent by the receiver after unsuccessful transmission and CI denotes that cooperation is not possible. For safety message, if S and R are not in the same network, then S transmits data through the CT. CT increases transmission range i.e. extends network coverage, but if there is no helper, then cooperation is not possible because the destination R is not reachable even with helper. If S and R are in the same network, then S transmits data through DT and S will avoid CT. Then S will wait for NACK. If S receives NACK, then it will be denoted as a failed transmission. If S receives NACK, then S will send safety messages through CT for the failed transmission. For non-safety data, S will transmit WSA and R will send WTI. If S gets CWSA and suitable helper, then S will transmit non-safety data through CT, otherwise DT.

Table 5.1 An algorithm to find the suitable data transmission mode for sm

If $(S, R) \notin U$
CT
else if $H_i \notin U_h$
C_I
end
end
If $(S, R) \in U$
DT
else if $R_{NACK} \in U_{NACK}$
CT
else if $H_i \notin U_h$
C_I
end
end
end

5.1.4 Channel Access

Due to the dynamic and open nature of VANETs, a random approach is suitable and efficient [75]. The random access mechanism i.e. CSMA/CA used in IEEE 802.11p is used by the proposed RECV-MAC protocol. Therefore, the RECV-MAC protocol is compatible with IEEE 802.11p.

When a vehicle has a packet to transmit, it starts to listen the channel. If the channel is listened idle for DCF inter frame space (DIFS) time, the vehicle transmits. Otherwise, the vehicle initiates a random backoff before transmitting to decrease collision probability. The vehicular node starts a backoff process by taking backoff value arbitrarily. It is decreased by 1 when the channel is listened idle in a slot time, and paused in the present value when the channel is listened busy, and resumed when the channel becomes idle for more than DIFS. The packet will be delivered when backoff is 0.

5.1.5 Three Party Handshake

Three party handshake among the sender (S), the receiver (R) and the helper (H) node or nodes for sm and nsd are presented in Figures 5.4 and 5.5, respectively. For safety messages, cooperation is initiated by the R by sending NACK to S. R broadcasts NACK and initializes cooperation for failed transmission. Then all neighboring nodes which get NACK will check their channel condition for the safety message transmission. If neighboring nodes have good channel condition for the safety message transmission, then they will offer to help by sending KTH. In Fig. 4, H_1 and H_2 send KTH to S since they have good channel condition to relay the safety message. After SIFS interval, S

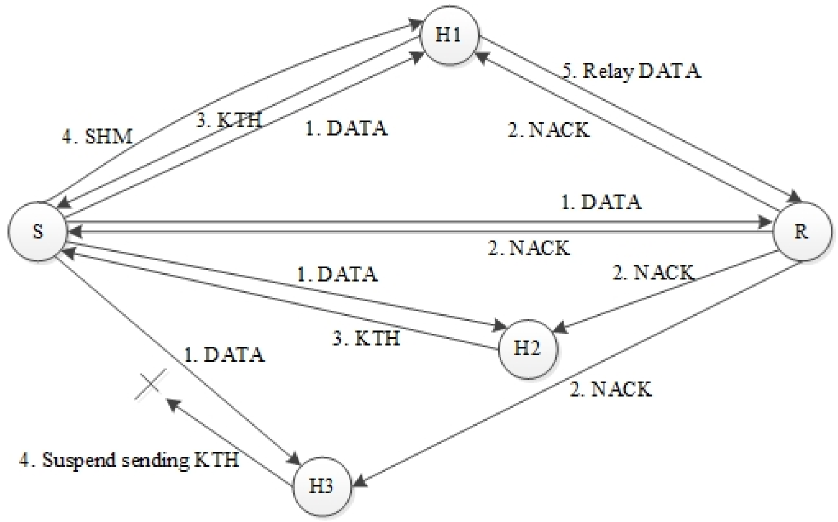

Figure 5.4 Three party handshake among the sender, the receiver and helper node or nodes for safety messages

will choose optimal helper among nodes which send KTH based on their SINR and S will send SHM to the optimal helper H_1. After hearing SHM, other nodes will suspend to send KTH for same NACK and H_3 suspends sending KTH for the same NACK. Then, the optimal helper H1 will send the safety message to R.

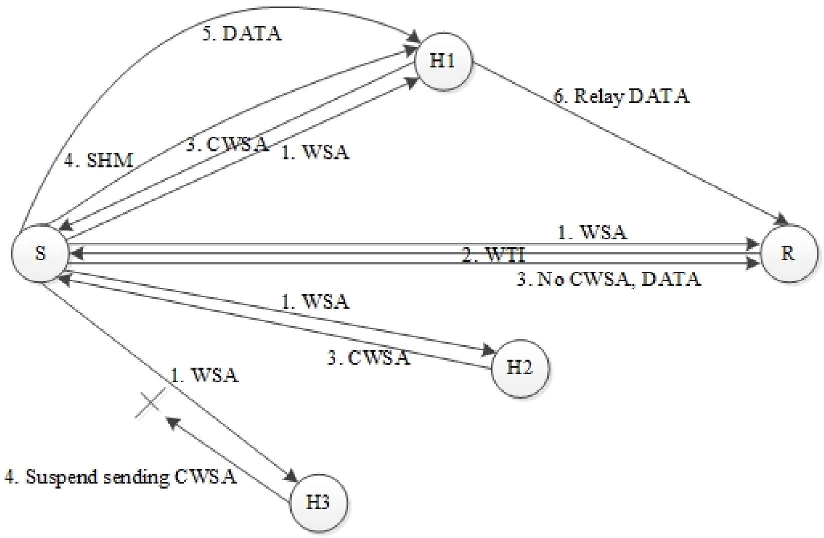

Figure 5.5 Three party handshake among the sender (WAVE provider), the receiver (WAVE user) and helper node or nodes for non-safety data

For non-safety data, WAVE provider (S) will broadcast WSA and offer services. WAVE user (R) will send WTI to S. If neighboring nodes have better channel condition, then they will send CWSA to S. H_1 and H_2 send CWSA to offer themselves as a WAVE helper as they have better channel condition. After SIFS interval, S will choose optimal WAVE helper among H_1 and H_2 based on their SINR. S will send SHM to the optimal WAVE helper H_1 as in Fig. 5. H_3 suspends sending CWSA for the same WTI after hearing

SHM. S will transmit the non-safety data to the WAVE user R through the optimal WAVE helper H_1.

5.1.6 Optimal Helper Selection

For both safety messages and non-safety data, optimal helper node will be chosen by the sender. Cooperation is initialized by the receiver for sm and by the helper for nsd transmission. The cooperation gain is contingent on the helper. When the number of helper is increased, the reliability of communication is also increased due to diversity gain [76].

For safety messages, the receiver (R) initiates cooperation by sending NACK. Then, neighboring nodes which have better channel condition send KTH to the sender (S). The S will choose optimal helper which has optimal SINR and S will send SHM to the optimal helper. For non-safety data, neighboring nodes which have better channel condition will send CWSA to WAVE provider (S) and initiate cooperation. The nodes which send CWSA to the S are WAVE helpers. The node which has optimal SINR among WAVE helpers will be considered as optimal WAVE helper. S will send SHM to the optimal WAVE helper. The neighboring nodes which offer to help in transmitting data by sending KTH or CWSA are helper. Helpers have better channel condition. Optimal helper is the helper which has optimal SINR among helpers [77–79].

5.1.7 Performance Analysis

Saturated condition is considered and assumed that NACKs and KTHs are successfully received. Same VANET scenario is considered which is mentioned in Section 2.2.1 from eq. (2.1) to eq. (2.6).

The Markov chain for the backoff technique is illustrated in Figure 2.1. Let P_t be the probability of transmission that a vehicular node sends a packet in a slot time which can be defined from eq. (2.13) as

$$P_t = b_0 = \frac{2}{CW+1}. \tag{5.1}$$

Collision occurs if at least one of the existing $N-1$ vehicular nodes is transmitting a packet in the identical slot time. Thus, P_c can be written as

$$P_c = 1-(1-P_t)^{N-1}. \tag{5.2}$$

The channel will be busy if minimum one vehicle is transmitting a packet within r_t.

Since N vehicular nodes compete for the transmission, P_b is

$$P_b = 1-(1-P_t)^N. \tag{5.3}$$

Let P_s be the probability of successful transmission that the current transmission is successful which can be written as

$$P_s = \frac{NP_t(1-P_t)^{N-1}}{P_b}C_{ch}, \tag{5.4}$$

where C_{ch} denotes the channel condition. The channel can be either in good or bad state modeled by a two state Markov chain model [80].

P_{d-CT} is the cooperation decision probability that the cooperative transmission decision is taken. The cooperative transmission decision will be taken when direct transmission fails and there is at least one suitable helper for cooperation. P_{d-CT} is given as

$$P_{d-CT} = P_c(1-P_h) \tag{5.5}$$

where P_h is the probability of not getting helper which can be given as

$$P_h = \frac{N-h}{N}, \tag{5.6}$$

where h is the number of helpers. As one vehicle is the sender and another vehicle is the receiver, h ranges from 0 to (N-2).

Let P_{s-CT} be the probability of successful transmission with cooperation that the packet transmission becomes successful with the cooperative transmission. If the transmission is successful after cooperative transmission, then the cooperation is advantageous. In cooperative communication approach, the transmission can be successful either direct transmission or cooperative transmission after failed transmission. P_{s-CT} is given as

$$P_{s-CT} = P_s + P_s(1-P_s)P_{d-CT}. \tag{5.7}$$

Using Eq. (5.5) - Eq. (5.6) in Eq. (5.7) Ps-CT can be obtained as

$$\begin{aligned} P_{s-CT} &= P_s + P_sP_c\,(1-P_s)\left(1-\tfrac{N-h}{N}\right) \\ &= P_s\left(1+\tfrac{P_c(1-P_s)h}{N}\right). \end{aligned} \tag{5.8}$$

Let T_e be the expected time spent by a vehicular node in each Markov state. T_e for both DT and CT can be given as

$$T_{e-DT} = (1 - P_b)T_{slot} + P_b P_s T_{s-DT} + P_b(1 - P_s)T_c, \tag{5.9}$$

$$T_{e-CT} = (1 - P_b)T_{slot} + P_b P_{s-CT} T_{s-CT} + P_b(1 - P_{s-CT})T_c, \tag{5.10}$$

where T_{s-DT} and T_{s-CT} are the time interval when a packet is successfully sent with direct and cooperative transmission, respectively, T_c is the duration of a collided transmission.

For the RECV-MAC protocol, T_{s-DT}, T_{s-CT}, and T_c of safety messages (sm) and non-safety data (nsd) can be written as

$$T_{s-DT(sm)} = \frac{L_h + L}{R_d} + T_{DIFS} + T_{delay}, \tag{5.11}$$

$$T_{s-CT(sm)} = \frac{L_h + L_{ch} + 2L}{R_d} + T_{DIFS} + 3T_{SIFS} + T_{delay} + T_{NACK} + T_{KTH} + T_{SHM}, \tag{5.12}$$

$$T_{s-DT(nsd)} = \frac{L_h + L}{R_d} + T_{DIFS} + T_{SIFS} + T_{WSA} + T_{WTI} + T_{delay}, \tag{5.13}$$

$$T_{s-CT(nsd)} = \frac{L_h + L_{ch} + 2L}{R_d} + T_{DIFS} + 3T_{SIFS} + T_{WSA} + T_{WTI} + T_{CWSA} + T_{SHM} + T_{delay}, \tag{5.14}$$

$$T_c = \frac{L_h + L}{R_d} + T_{DIFS} + T_{delay}, \tag{5.15}$$

where L_h and L_{ch} are the length of MAC and PHY layer header and cooperation header respectively, L denotes the transmitted packet size and R_d indicates the data transmission rate. $T_{NACK}, T_{KTH}, T_{WSA}, T_{WTI}, T_{CWSA}, T_{SHM}$ is the time required for NACK, KTH, WSA, WTI, CWSA, and SHM, respectively. T_{delay} is the propagation delay.

Let $O_{s-CT(sm)}$ and $O_{s-CT(nsd)}$ be the overhead initialized by the RECV-MAC protocol for sm and nsd in CT mode, respectively which can be written as

$$O_{s-CT(sm)} = \frac{L_{ch}}{R_d} + 3T_{SIFS} + T_{NACK} + T_{KTH} + T_{SHM}, \tag{5.16}$$

$$O_{s-CT(nsd)} = \frac{L_{ch}}{R_d} + 2T_{SIFS} + T_{CWSA} + T_{SHM}. \tag{5.17}$$

5.1.7.1 Throughput and PDR Analysis

Let S be the normalized throughput. S is the data transmitted over the average period of a slot time which can be defined as

$$S = \frac{E[transmittedpayloadlengthinaslottime]}{E[durationofaslottime]} = \frac{E[p]}{T_e}. \tag{5.18}$$

Therefore, S for direct transmission S_{DT} and cooperative transmission S_{CT} can be given as follows

$$S_{DT} = \frac{P_s P_{busy} L}{\left(1-P_{busy}\right) T_{slot} + P_{busy} P_s T_{s-DT} + P_{busy}(1-P_s)T_c}, \tag{5.19}$$

$$S_{CT} = \frac{P_{s-CT} P_{busy} L}{P_h[(1-P_{busy})T_{slot} + P_{busy} P_{s-CT} T_{s-CT} + P_{busy}(1-P_{s-CT})T_c]}. \tag{5.20}$$

Hence the normalized system throughput gain attained due to cooperative transmission can be computed as

$$S_{\text{gain}} = \frac{S_{CT} - S_{DT}}{S_{DT}}. \tag{5.21}$$

The packet dropping rate (PDR) for DT is

$$PDR_{DT} = (1-P_s). \tag{5.22}$$

A packet will be transmitted with CT after the failure of DT. If C_A denotes the number of cooperation attempts, the PDR for CT is

$$PDR_{CT} = (1-P_{s-CT})^{C_A}. \tag{5.23}$$

Therefore, the PDR gain achieved due to cooperative transmission is

$$PDR_{\text{gain}} = \frac{-(PDR_{CT} - PDR_{DT})}{PDR_{DT}}. \tag{5.24}$$

5.1.7.2 Delay Analysis

In this section details delay analysis is presented.

A. Average Access Delay

$E[D_{access}]$ is the average access delay that is the mean time duration for a packet transmission from contending for the channel to the successful transmission of the packet or drop of the packet. Two events can happen, either the packet is successfully transmitted whether a collision happens and no collision happens or the packet is dropped because of collision. $E[D_{access}]$ for both DT and CT can be given as

$$E\left[D_{access-DT}\right] = E\left[T_{waiting-DT}\right] P_c \left(1 - P_c\right) + E\left[T_{waiting-DT}\right] P_c, \tag{5.25}$$

$$E\left[D_{access-CT}\right] = E\left[T_{waiting-CT}\right] P_c \left(1 - P_c\right) + E\left[T_{waiting-CT}\right] P_c, \tag{5.26}$$

where $E[T_{waiting}]$ is the mean waiting time that is the average time interval at the backoff period. Backoff counter is chosen randomly from [0, CW_0 -1], $E[T_{waiting}]$ for both DT and CT is

$$E[T_{waiting-DT}] = \frac{(CW-1)}{2} T_{e-DT}, \tag{5.27}$$

$$E[T_{waiting-CT}] = \frac{(CW-1)}{2} T_{e-CT}. \tag{5.28}$$

B. Packet Drop Probability

The packet will be dropped because of collision. P_{drop} is the probability that a packet is dropped which can be given as

$$P_{drop} = P_c. \tag{5.29}$$

Let P_{fdrop} be the final packet drop probability that a packet is dropped finally. Therefore, the mean number of dropped packets in relation to a successful transmission is

$$E[X_{dpacket}] = \frac{P_{fdrop}}{1 - P_{fdrop}}. \tag{5.30}$$

C. Average Time to Drop a Packet

$E[T_{drop-DT}]$ is the average packet drop time that the mean time length to drop a packet which can be written for both DT and CT as

$$E\left[T_{drop-DT}\right] = E\left[X_{drop}\right] T_{e-DT}, \tag{5.31}$$

$$E\left[T_{drop-CT}\right] = E\left[X_{drop}\right] T_{e-CT}, \tag{5.32}$$

where $E[X_{drop}]$ denotes the mean number of slot times for a packet which is dropped:

$$E\left[X_{drop}\right] = \frac{CW+1}{2}. \tag{5.33}$$

D. Average Packet Delay

The average packet delay $E[D]$ is the mean time duration from the time when the packet is prepared to be transmitted in its MAC queue up to the time of successful transmission. In computing $E[D]$, the time interval of a packet which is dropped will not be counted. Therefore, $E[D]$ can be computed for both DT and CT as

$$E[D_{DT}] = E[T_{interval-DT}] - E\left[X_{dpacket}\right]E[T_{drop-DT}], \tag{5.34}$$

$$E[D_{CT}] = E[T_{interval-CT}] - E\left[X_{dpacket}\right].E[T_{drop-CT}], \tag{5.35}$$

where $E[T_{interval}]$ is the average packet interval that is the mean time span at one receiver between two successful reception of packets which can be achieved from the throughput for both DT and CT as

$$E[T_{interval-DT}] = \frac{NE[p]}{S} = NT_{e-DT}, \tag{5.36}$$

$$E[T_{interval-CT}] = \frac{NE[p]}{S} = NT_{e-CT}. \tag{5.37}$$

Using Eq. (5.30) - Eq. (5.37) the E[D] for both DT and CT can be expressed as

$$E[D_{DT}] = T_{e-DT}\left(N - \frac{P_{fdrop}}{1-P_{fdrop}}\frac{CW+1}{2}\right), \tag{5.38}$$

$$E[D_{CT}] = T_{e-CT}\left(N - \frac{P_{fdrop}}{1-P_{fdrop}}\frac{CW+1}{2}\right). \tag{5.39}$$

5.1.8 Numerical Results

The performance of the RECV-MAC protocol is assessed and the theoretical analysis is verified in this section. The numerical analysis is performed in MATLAB for a VANET of randomly distributed 100 vehicles running on a two lane road. The numerical analysis model considers key MAC behavior of the IEEE 802.11p in VANETs. Broadcast mode of safety messages (sm) and unicast mode of non-safety data (nsd) is considered. The proposed RECV-MAC protocol is compared with the traditional MAC model which is based on the IEEE 802.11p. Moreover, a quantitative comparison with existing cooperative MAC mechanisms is provided. Table 5.2 presents the value of parameters utilized in the numerical analysis.

Figure 5.6 demonstrates throughput against number of vehicles in normal case as well

Table 5.2 Value of parameters utilized in numerical analysis

Parameters	**Value**
$T_{slot}, T_{delay}, T_{SIFS}, T_{DIFS}$ μs	20, 1, 10, 50
NACK, KTH, SHM, WTI, WSA, CWSA (bytes)	20, 26, 24, 24, 28, 25, 27
L_h, L (bytes)	50, 512
R_c, R_d, λ (Mbps)	1, 11, 0.5
m_r, m_{rsm}, m_{rnsd}	7, 2, 7
W_O	64
β (m)	10
v (km/h)	20-140
D_T (veh/m)	0-0.5
Width of a lane (m)	5
r_t (m)	500

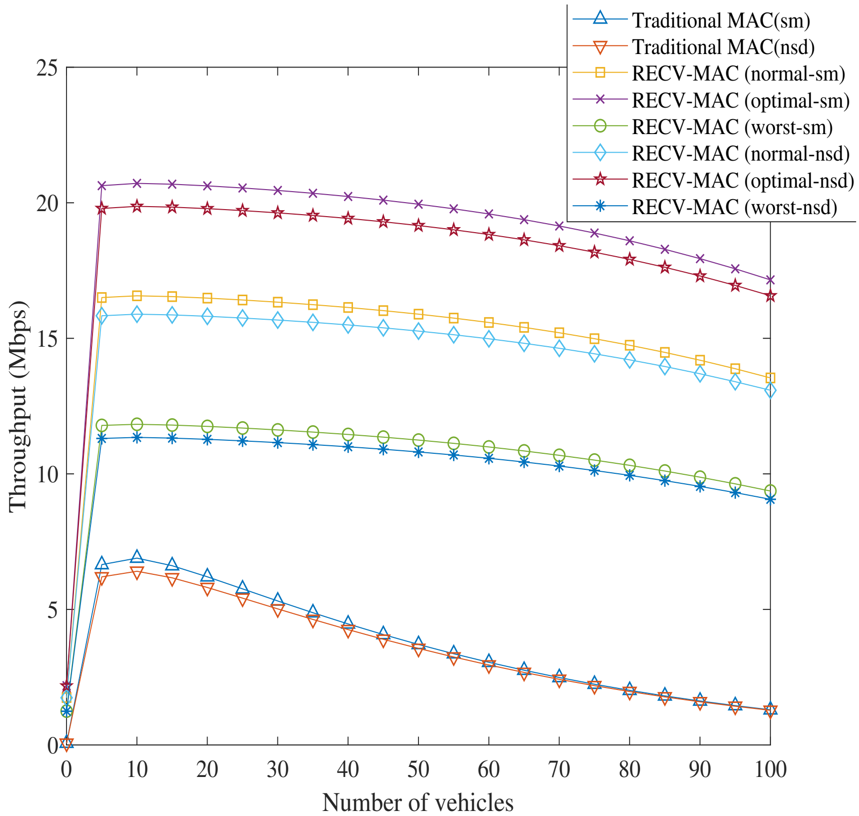

Figure 5.6 Throughput versus number of vehicles, Ph = 0.5 in normal case, Ph 0.4 in optimal case, Ph 0.7 in worst case

as in the case of getting the helper with high probability and low probability. There is a remarkable improvement of throughput in the RECV-MAC protocol for both sm and nsd transmission in VANETs. Throughput increases until a certain point then throughput decreases which can be observed in Figure 5.6. Since fewer number of vehicles may not cause collision, throughput starts to increase with increasing vehicles, but after the number of vehicular nodes further increases, then more vehicles would cause more collisions and throughput falls. It is also noticeable that higher probability of getting helper will increase throughput, since S-R link will be more reliable to transmit the packet and the transmission will be faster with good channel condition through cooperation. The throughput for the RECV-MAC protocol in optimal case is higher than normal due to the availability of helper. Nevertheless, the opposite scenario is perceived in worst case due to the unavailability of helper. More cooperation gain can be achieved with the more helpers.

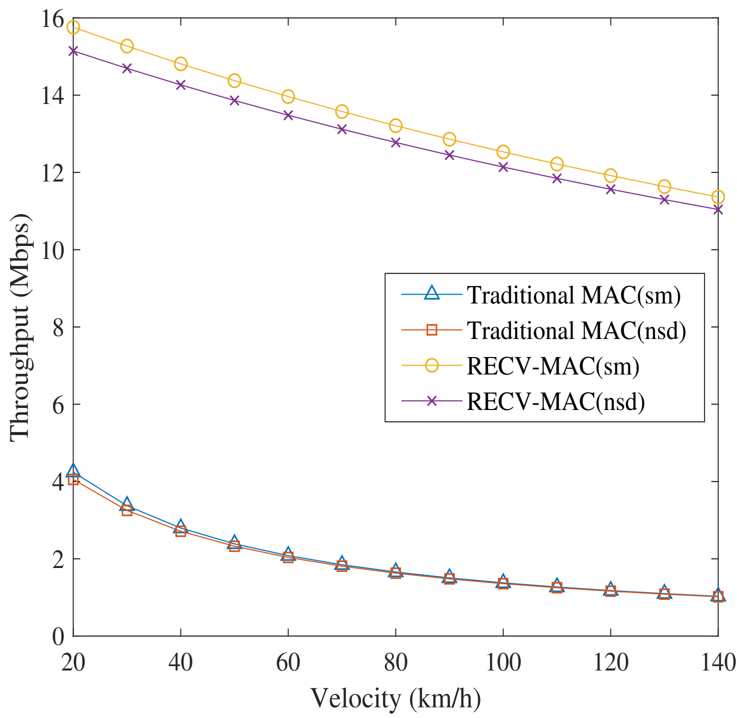

Figure 5.7 Throughput against velocity

Figure 5.7 depicts the throughput versus vehicle velocity. The throughput decreases with increasing velocity because high relative mobility among vehicles can result in rapid topology changes which cause unstable communications. Nevertheless, RECV-MAC protocol improves throughput for both sm and nsd transmission in VANETs under different vehicle velocity.

Figure 5.8 shows the packet dropping rate (PDR) versus number of vehicles. PDR is rising with increasing number of vehicles as the probability of collision increases. When there are more vehicular nodes, the possibility of packet arrival increases which will result in more collisions. However, the PDR gain of the RECV-MAC protocol is significant. The RECV-MAC protocol ensures reliable transmission by decreasing PDR. Moreover, the comparison between different contention window sizes (CW) is provided. When CW is larger, extended back-off time lessens collision as well as reduce

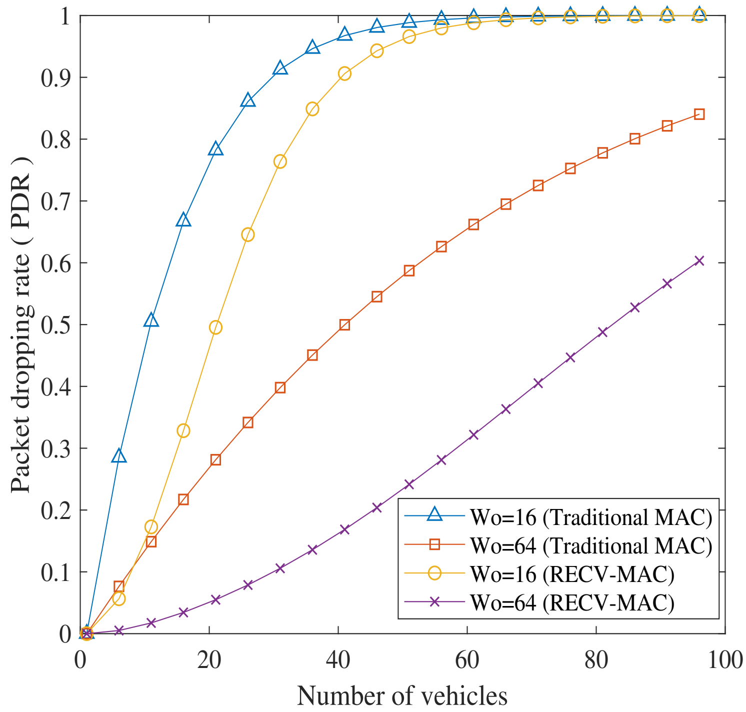

Figure 5.8 Packet dropping rate (PDR) against number of vehicles

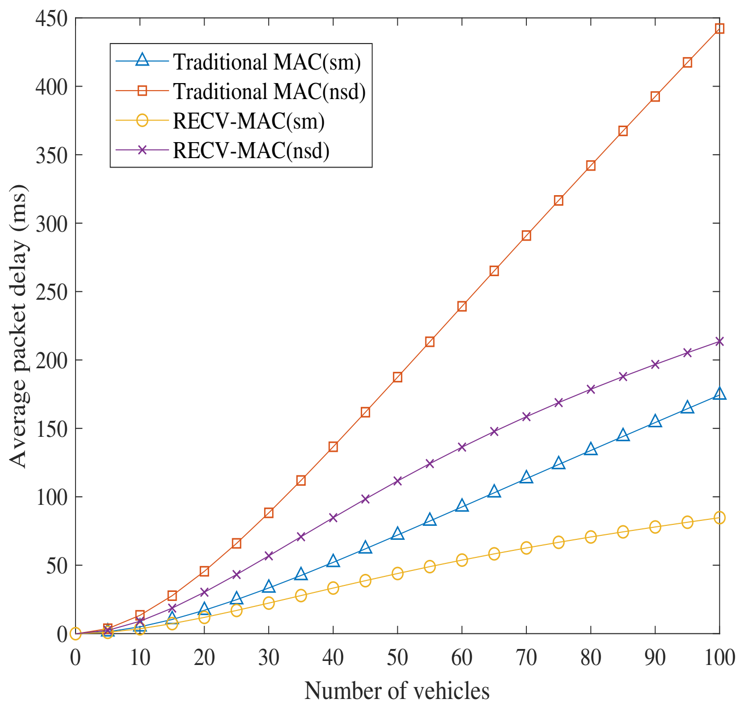

Figure 5.9 Average packet delay against number of vehicles

packet loss, thus the PDR is decreased.

Figure 5.9 shows the average packet delay against number of vehicles. The average

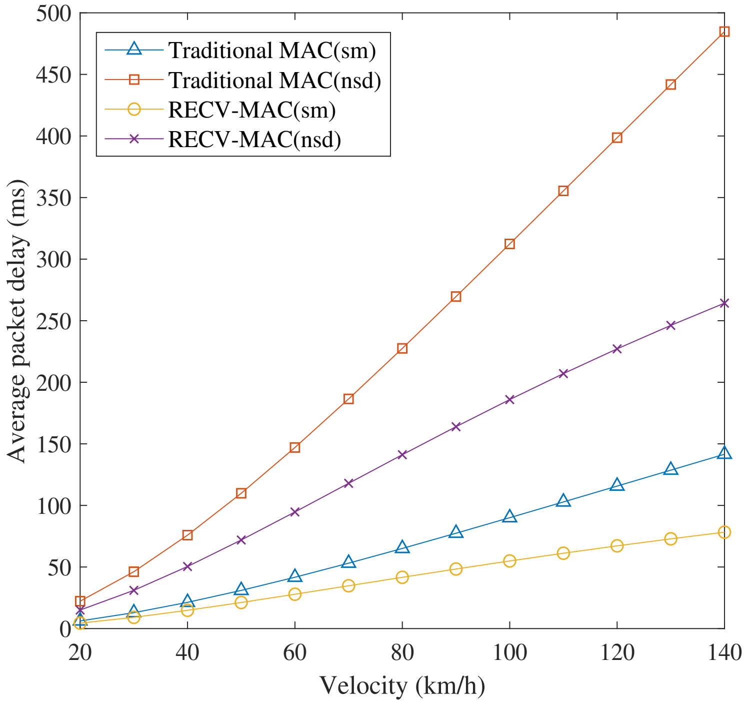

Figure 5.10 Average packet delay versus velocity

packet delay goes up with the number of vehicles because there would be more packets to transmit. For transmission, these additional packets would compete for the channel in the identical time slot which results in enlarged channel busy probability as well as collision probability. Therefore, the average packet delay is increased. Since RECV-MAC decreases the final packet drop probability and increases the probability of successful transmission, the average packet delay is reduced. Figure 5.10 depicts average packet delay versus velocity. Average packet delay is increasing radically while the velocity is increasing because topology changes promptly with mobility which causes collision as well as packet loss due to frequent link breakage and unstable communications. However, RECV-MAC protocol decreases delay both for sm and nsd transmission in VANETs and fulfills the requirement of latency 100 ms for sm.

Under the same network scenario in existing cooperative MAC mechanisms, maximum throughput achieved is about 3.5 Mbps, 3.5 Mbps, 6 Mbps, 7 Mbps, and 8 Mbps in [55, 65, 68, 69], and [67], respectively. On the other side, in RECV-MAC protocol achieves maximum throughput about 20 Mbps. Delay analysis is not provided in [56, 60], and [65, 66]. Delay constraint of safety messages is not satisfied in [63, 64], and [68]. Alternatively, the RECV-MAC protocol fulfills the 100 ms delay constraint of safety messages in VANETs.

5.2 QoS aware RECV-MAC Protocol

A QoS aware reliable and efficient cooperative MAC protocol for VANETs (qRECV-MAC) is designed. RECV-MAC protocol can ensure QoS by applying IEEE 802.11p EDCAF. Channel access mechanism is hinge on IEEE 802.11p EDCA technique for different ACs to ensure desired QoS at the MAC layer.

5.2.1 Performance Analysis

Now P_t can be written from eq. (5.1) as

$$P_t[AC] = b_0 = \frac{2}{CW[AC]+1}. \tag{5.40}$$

P_c can be given from eq. (5.2) as

$$P_c[AC] = 1-(1-P_t[AC])^{N-1}. \tag{5.41}$$

P_b can be written from eq. (5.3) as

$$P_b[AC] = 1-(1-P_t[AC])^{N}. \tag{5.42}$$

P_s can be written from eq. (5.4) as

$$P_s[AC] = \frac{NP_t[AC](1-P_t[AC])^{N-1}}{P_b[AC]}C_{ch}, \tag{5.43}$$

P_{s-DT} can be given from eq. (5.8) as

$$P_{s-CT}[AC] = P_s[AC]\left(1+\frac{P_c[AC](1-P_s[AC])h}{N}\right). \tag{5.44}$$

T_e for both DT and CT can be given from eq. (5.9) and eq. (5.10), respectively as

$$T_{e-DT}[AC] = (1-P_b[AC])T_{slot} + P_b[AC]P_s[AC]T_{s-DT} + P_b[AC](1-P_s[AC])T_c, \tag{5.45}$$

$$T_{e-CT}[AC] = (1-P_{busy}[AC])T_{slot} + P_{busy}[AC]P_{s-CT}[AC]T_{s-CT} + P_{busy}[AC](1-P_{s-CT}[AC])T_c. \tag{5.46}$$

T_{s-DT}, T_{s-CT}, and T_c of safety messages (sm) and non-safety data (nsd) can be written as

$$T_{s-DT(sm)} = \frac{L_h+L}{R_d} + T_{AIFS}[AC] + T_{delay}, \tag{5.47}$$

$$T_{s-CT(sm)} = \frac{L_h + L_{ch} + 2L}{R_d} + T_{AIFS}[AC] + 3T_{SIFS} + T_{delay} + T_{NACK} + T_{KTH} + T_{SHM}, \quad (5.48)$$

$$T_{s-DT(nsd)} = \frac{L_h + L}{R_d} + T_{AIFS}[AC] + T_{SIFS} + T_{WSA} + T_{WTI} + T_{delay}, \quad (5.49)$$

$$T_{s-CT(nsd)} = \frac{L_h + L_{ch} + 2L}{R_d} + T_{AIFS}[AC] + 3T_{SIFS} + T_{WSA} + T_{WTI} + T_{CWSA} + T_{SHM} + T_{delay}, \quad (5.50)$$

$$T_c = \frac{L_h + L}{R_d} + T_{AIFS}[AC] + T_{delay}. \quad (5.51)$$

S for direct transmission S_{DT} and cooperative transmission S_{CT} can be given from eq. (5.19) and eq. (5.20), respectively as follows

$$S_{DT} = \frac{P_s[AC]P_b[AC]L}{(1 - P_b[AC])\,T_{slot} + P_b[AC]P_s[AC]T_{s-DT} + P_b[AC](1 - P_s[AC])T_c}, \quad (5.52)$$

$$S_{CT} = \frac{P_{s-CT}[AC]P_b[AC]L}{P_h[(1 - P_b[AC])T_{slot} + P_b[AC]P_{s-CT}[AC]T_{s-CT} + P_b[AC](1 - P_{s-CT}[AC])T_c]}. \quad (5.53)$$

5.2.2 Numerical Results

The performance of the QoS aware RECV-MAC (qRECV-MAC) protocol is evaluated in this section. The numerical results are obtained by using MATLAB. A vehicular network of 100 arbitrarily distributed vehicles. The transmission range is 500 m. We assume that all the vehicle's velocity in a cluster is nearly same and the velocity is 100 km/h. Key MAC behavior of the IEEE 802.11 broadcast nature in VANETs is considered in the numerical analysis. The value of parameters utilized in the numerical analysis is given in Table 5.3.

Figures 5.11 presents throughput against number of vehicles. Throughput increases with increment of the number of vehicles until a certain range. After that throughput starts to fall because more number of packets will contend for transmission which will increase collision. Figures 5.12 shows throughput against velocity. Throughput decreases with the increase of velocity because high velocity changes topology rapidly which makes communication unstable. Moreover, RECV-MAC protocol has higher throughput than traditional MAC protocol. It is also noticeable that RECV-MAC

Table 5.3 Value of parameter utilized in numerical analysis

Parameter	Value	Parameter	Value
$CW_{min}[0]$	3	$CW_{min}[2]$	7
$CW_{max}[0]$	7	$CW_{max}[2]$	1023
$CW_{min}[1]$	3	$CW_{min}[3]$	15
$CW_{max}[1]$	15	$CW_{max}[3]$	1023
$AIFSN[0]$	2	$AIFSN[2]$	6
$AIFSN[1]$	3	$AIFSN[3]$	9
T_{slot}, T_{delay} μs	20, 1	T_{SIFS}	10
L_h, L (bytes)	50, 512	R_c, R_d	1, 11
RTS, CTS, ACK (bytes)	20, 14, 14	v (km/h)	100
D_T (veh/km/lane)	120	r_t (m)	500

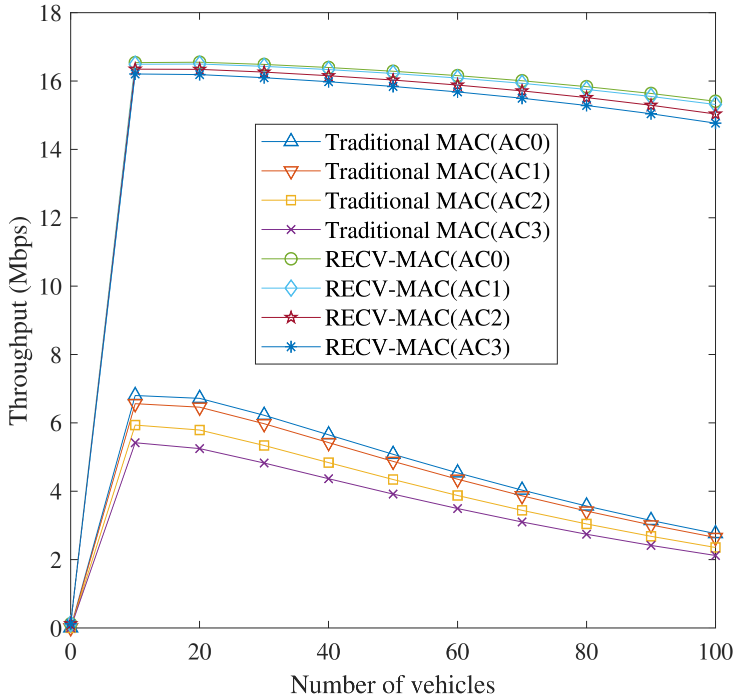

Figure 5.11 Throughput against number of vehicles

protocol ensures QoS. AC0 has higher throughput than AC1, AC1 has higher throughput than AC2, and AC2 has higher throughput than AC3. Different EDCA parameters ensure QoS among different ACs. The qRECV-MAC protocol improves the system throughput and ensures desired QoS.

From Figure 5.11 to Figure 5.12, it is comprehended that throughput of AC0 is higher than AC1, AC1 is higher than AC2, and AC2 is higher than AC3, and in the case of delay AC0 is lower than AC1, AC1 is lower than AC2, and AC2 is lower than AC3. The ACO has highest throughput but lowest delay and AC3 has lowest throughput but highest delay. For throughput, AC0>AC1>AC2>AC3 and for delay,

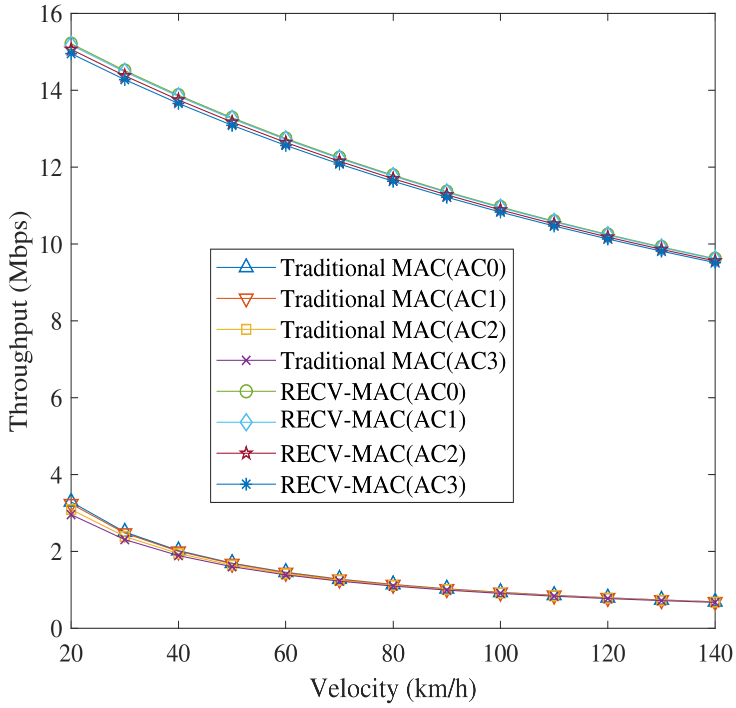

Figure 5.12 Throughput versus velocity

AC0<AC1<AC2<AC3. The backoff process makes it possible. Since T_{AIFS} is different due to different AIFSN value, packets of different ACs have different T_{AIFS}, different ACs have different backoff. AIFSN value of ACO is lowest and AC3 is highest. For AIFSN value, AC0<AC1<AC2<AC3. Not only AIFSN value but also CW_{min} and CW_{max} influence backoff process. The lowest CW_{min} and CW_{max} has AC0 and highest CW_{min} and CW_{max} has AC3. Therefore, due to T_{AIFS}, CW_{min} and CW_{max}, packets in AC0 is transmitted first, then AC1, then AC2, then AC3 which results in highest throughput in AC0 and lowest delay in AC0, and so on.

6
Optimization and Complexity Analysis

6.1 Optimization

In this section, optimization of IEEE 802.11p, IEEE 802.11, and CB-MAC protocol are presented.

6.1.1 Optimization of IEEE 802.11p

In vehicular ad hoc networks (VANETs), throughput changes with variation of traffic, contention window (CW) size, and vehicle velocity. If any of these parameters is changed, throughput changes and even throughput may become negligible. Since the number of vehicles and vehicle velocity are not controllable, CW size will be optimized to maximize throughput. Here throughput is optimized for highly important safety messages (sm) in VANETs by optimizing CW size with respect to number of vehicles and vehicle velocity. If any of these parameters (number of vehicles and/or vehicle velocity) changes, CW size will be dynamically adjusted to keep throughput in maximum level. In order to get optimum throughput S, eq. (2.41) can be rearranged as

$$S = \frac{L}{T_s - T_c + \frac{P_b(T_c - T_{slot}) + T_{slot}}{P_s P_b}}. \tag{6.1}$$

Since L, T_s, T_c, and T_{slot} are constants, S will be maximum when the following quantity is optimized:

$$\frac{P_s P_b}{P_b + \frac{T_{slot}}{(T_c - T_{slot})}} = \frac{N P_t (1-P_t)^{N-1}}{\left(1-(1-P_t)^N\right) + k}, \tag{6.2}$$

where $k = \frac{T_{slot}}{T_{col} - T_{slot}}$. Taking the derivative of (6.2) with respect to P_t and equalizing to 0,

$$kNP_t - k + (1-P_t)^N + NP_t - 1 = 0. \tag{6.3}$$

Under the condition Pt«1, the following series expansion takes place [30]:

$$(1-P_t)^N \cong 1 - NP_t + \frac{N(N-1){P_t}^2}{2}. \tag{6.4}$$

Then eq. (6.3) can be simplified as

$$kNP_t - k + \frac{N(N-1)P_t^{\,2}}{2} = 0. \tag{6.5}$$

Therefore, optimum P_t can be derived from (6.5) as

$$P_t = \frac{\sqrt{kN(kN+2N-2)} - kN}{N(N-1)}. \tag{6.6}$$

where $N > 1$. After taking second derivative of (6.1) with respect to P_t, we get negative value of P_t because right part of the expression is always >1 that is

$$P_t = 1 - \sqrt[N-1]{k+1}, \tag{6.7}$$

which shows it is the maximum P_t.

Let X be the mean vehicular node population in the road segment. According to Little's law

$$X = \lambda T_e, \tag{6.8}$$

Using eq. (2.3) to (2.4) in (6.8), we can obtain

$$X = n_L J_T \left(1 - \frac{v}{v_f}\right) v T_e. \tag{6.9}$$

The average number of vehicular nodes in transmission range (r_t) can be expressed as [81]

$$E[N] = X r_t. \tag{6.10}$$

By using (2.13) and (6.6), the optimum CW can be obtained for IEEE 802.11p as:

$$CW_{opt-IEEE802.11p} \approx \left\lceil \frac{2n_L k_{jam}\left(1 - \frac{v}{v_f}\right) v T_e R_t (N-1)}{\sqrt{kN(kN+2N-2)} - kN} - 1 \right\rceil, \tag{6.11}$$

where $\lceil . \rceil$ denotes ceil operation.

By using the optimum value of CW which will adopt the optimum value of P_t, the optimum throughput S can be obtained as

$$S = \frac{L}{T_s - T_c + \frac{(1-(1-P_{t\_opt})^N)(T_c - T_{slot}) + T_{slot}}{\left\lceil n_L J_T\left(1-\frac{v}{v_f}\right) v T_e \right\rceil r_t P_{t\_opt}(1-P_{t\_opt})^{N-1}}}. \tag{6.12}$$

The simulation is accomplished with MATLAB and SUMO. Firstly, microscopic mobility model is produced in SUMO, then output of SUMO is used as input to MATLAB and simulation results are obtained by 1000 Monte Carlo iterations. Figure 6.1 shows the area map and traffic simulation of the area considered in SUMO. The broadcast nature of safety messages is considered. Table 6.1 provides the parameter values utilized in the simulation. N is 100 for IEEE 802.11p in Figure 6.3 and Figure 6.4. The CW size is 64 for IEEE 802.11p.

Table 6.1 Parameter values used in simulation

Parameter	Value
$T_{slot}, T_{delay}, T_{SIFS}, T_{DIFS}$ μs	20, 1, 10, 50
L_h, L (bytes)	50, 100
v, v_f (km/h)	0-120, 160
R_d (Mbps)	11
N, m_r	0-150, 0-9
Maximum vehicle velocity (m/s)	14
J_T (veh/m)	120
r_t (m)	500

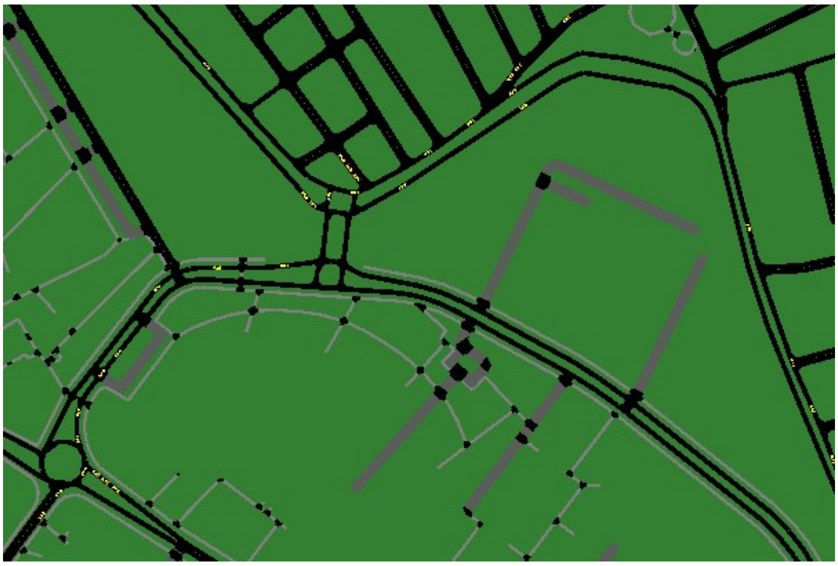

Figure 6.1 Traffic simulator view of Yildiz Technical University (YTU) of Davutpasa Campus, Istanbul in SUMO 1.2.0

The throughput against number of vehicles is demonstrated in Figure 6.2. Throughput increases with increase in the number of the vehicles until a certain point, then the throughput starts to fall. Since there would not be collision until certain traffic, but after that when more packets will be transmitted in the same time slot there would be more collision. It is noticeable that the throughput is always in maximum level because CW size, and v are dynamically adjusted with the variation of N.

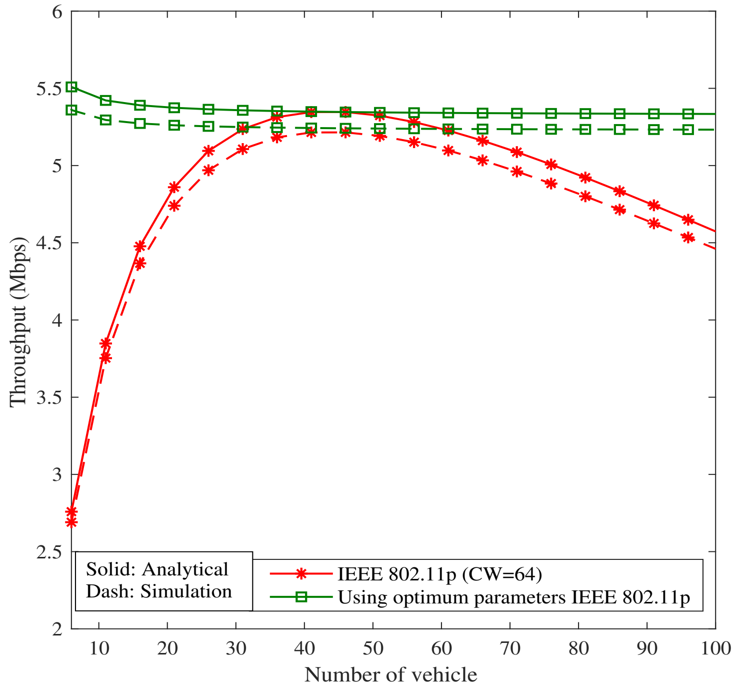

Figure 6.2 Throughput against number of vehicles

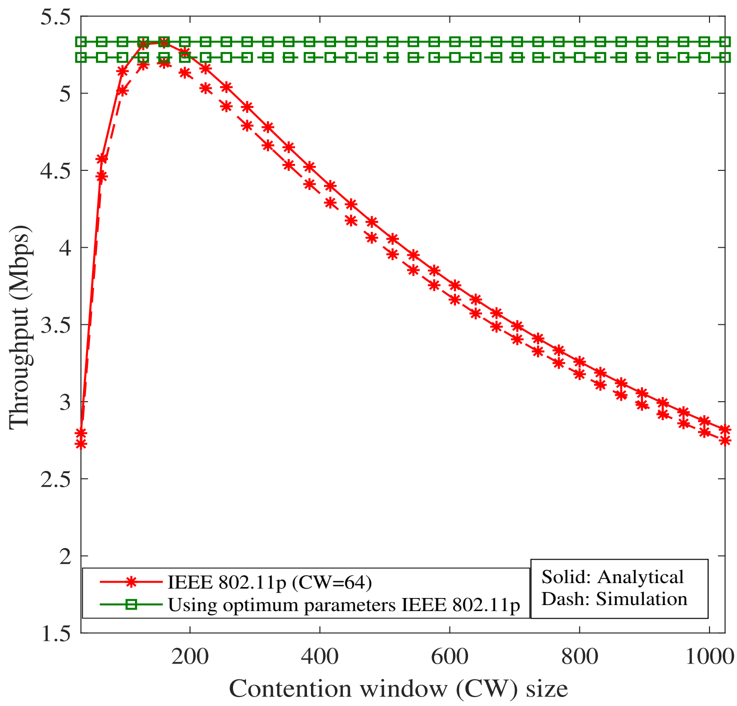

Figure 6.3 Throughput against CW size

Figure 6.3 shows throughput against CW size. The backoff time is small when the CW size is small which results in collision. Therefore, throughput is increased with the increase of CW size until a certain limit. If CW size further increases, the backoff time will increase which decreases throughput. N, and v are dynamically adjusted with the variation of CW size which results in maximum throughput.

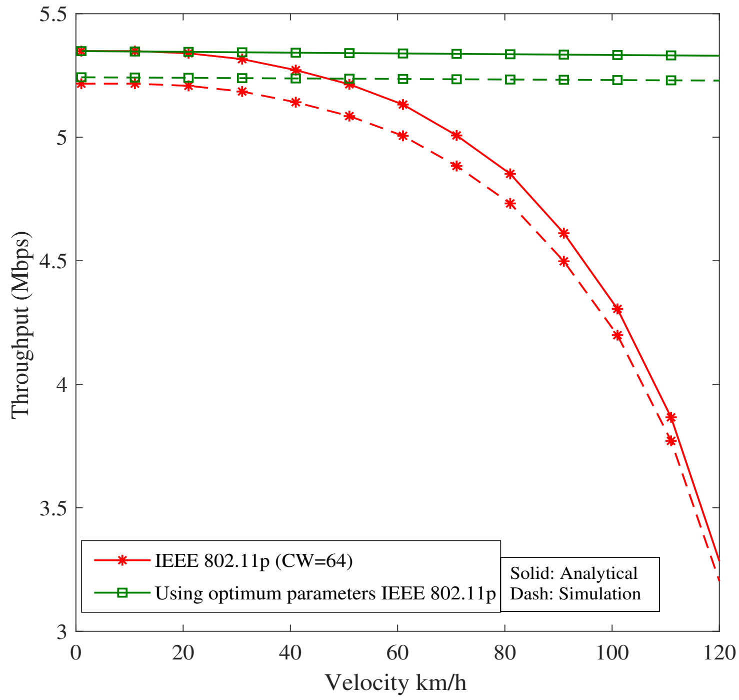

Figure 6.4 Throughput versus vehicle velocity

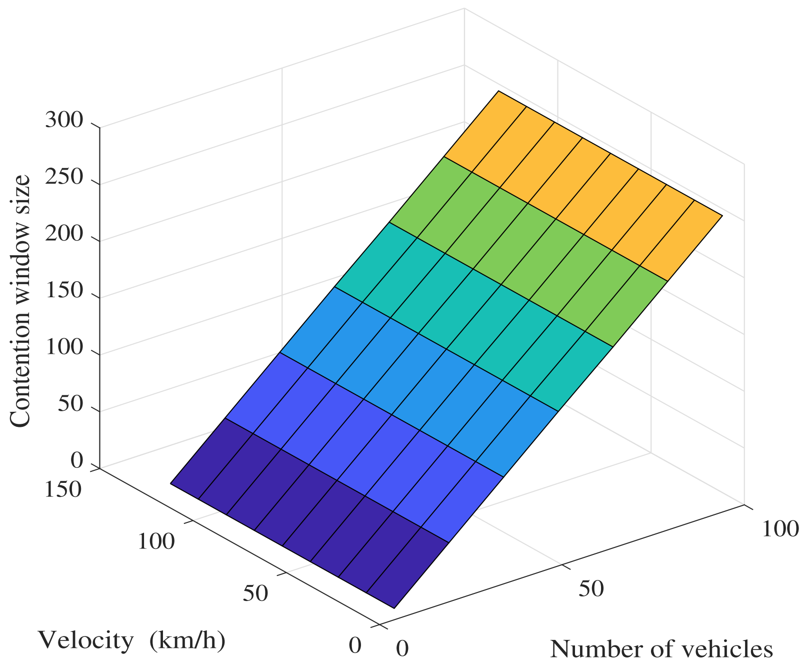

Figure 6.5 Optimum parameters variations in 3D

Figure 6.4 presents throughput against vehicle velocity. Throughput is decreasing when the vehicle velocity increases. Since vehicle mobility changes network topology rapidly which results in unstable communications and cause collision and packet loss. N, and CW size are dynamically adjusted with the variation of vehicle velocity which keep the maximum throughput.

Optimum parameters variations in 3D is presented in Figure 6.5. Optimum CW size is taken based on the number of vehicles and velocity. With the increase of number of vehicles and the velocity, CW size is increasing to decrease collision probability which will maximize throughput.

6.1.2 Optimization of IEEE 802.11

Optimum transmission probability P_t can be derived from (6.6). By using (3.8) and (6.6), the optimum CW can be obtained as:

$$CW_{opt-IEEE802.11} \approx \left\lceil \left(\frac{2n_L k_{jam}\left(1-\frac{v}{v_f}\right) v T_e R_t (N-1)}{\sqrt{kN(kN+2N-2)}-kN} - 1 \right) / 1 + m_r \right\rceil, \tag{6.13}$$

where $\lceil . \rceil$ denotes ceil operation.

By using the optimum value of CW which will adopt the optimum value of P_t, the optimum throughput S is obtained as

$$S = \frac{L}{T_s - T_c + \frac{(1-(1-P_{t\_opt})^N)(T_c - T_{slot}) + T_{slot}}{\left[n_L J_T\left(1-\frac{v}{v_f}\right) v T_e\right] r_t P_{t\_opt}(1-P_{t\_opt})^{N-1}}}. \tag{6.14}$$

The simulation is accomplished with MATLAB and SUMO. Firstly, microscopic mobility model is produced in SUMO, then output of SUMO is used as input to MATLAB and simulation results are obtained by 1000 Monte Carlo iterations. Figure 6.1 shows the area map and traffic simulation of the area considered in SUMO. The broadcast nature of safety messages is considered. Table 6.2 provides the parameter values utilized in the simulation. m_r is 5 in all figures. N is 100 in Figure 6.8 and Figure 6.9. The CW size is 64 for IEEE 802.11.

The throughput versus number of vehicles is demonstrated in Figure 6.6. Performance of IEEE 802.11 is not efficient for safety messages because RTS/CTS mechanism of the IEEE 802.11 is inactive in broadcast mode as RTS/CTS mechanism requires CTS after RTS. Thus, when message is broadcast to all vehicles, all vehicles have to send CTS. Hence, simultaneous CTS transmission will cause more collisions. Throughput goes up

Table 6.2 Parameter values used in simulation

Parameter	Value
$T_{slot}, T_{delay}, T_{SIFS}, T_{DIFS}$ μs	30, 3, 10, 50
RTS, CTS, ACK (bytes)	26, 20, 14
v, v_f (km/h)	0-120, 160
R_c, R_d (Mbps)	1, 11
N, m_r	0-150, 0-9
L_h, L (bytes)	50, 100
Maximum vehicle velocity (m/s)	14
J_T (veh/m), r_t (m)	120, 500

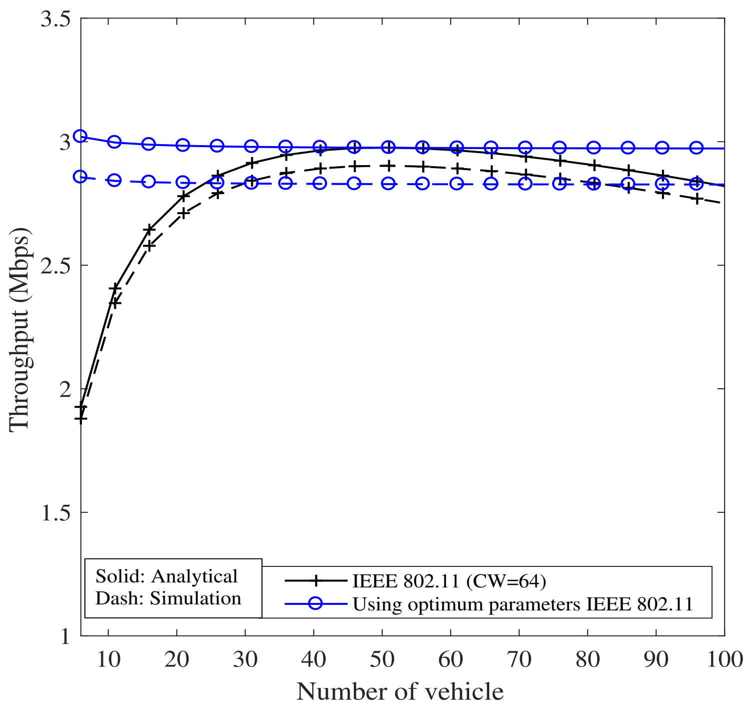

Figure 6.6 Throughput against number of vehicles

with increase in the number of the vehicles until a certain point, then the throughput starts to fall. Since there would not be collision until certain traffic, but after that when more packets will be transmitted in the same time slot there would be more collision. It is noticeable that the throughput is always in maximum level because CW size, m_r, and v are dynamically adjusted with the variation of N.

Figure 6.7 shows throughput versus CW size. The backoff time is small when the CW size is small which results in collision. Therefore, throughput is increased with the increase of CW size until a certain limit. If CW size further increases, the backoff time will increase which decreases throughput. N, m_r, and v are dynamically adjusted with the variation of CW size which results in maximum throughput.

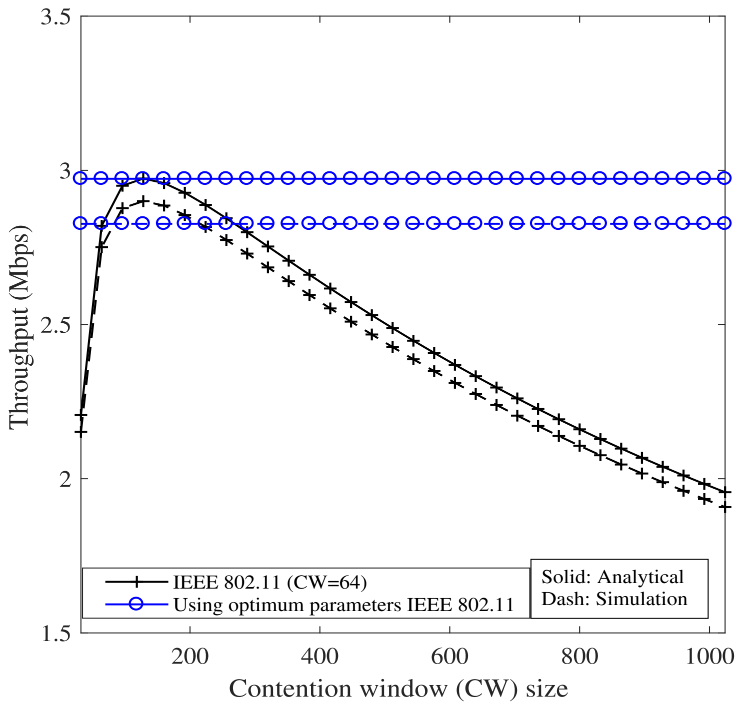

Figure 6.7 Throughput against CW size

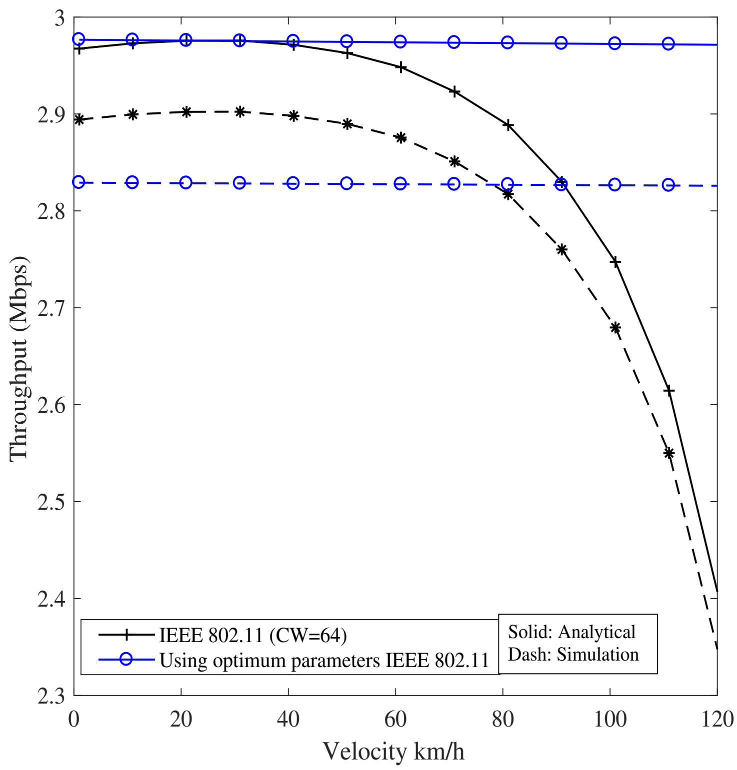

Figure 6.8 Throughput versus vehicle velocity

Figure 6.8 presents throughput against vehicle velocity. Throughput is decreasing when the vehicle velocity increases. Since vehicle mobility changes network topology rapidly which results in unstable communications and cause collision and packet loss. N, m_r, and CW size are dynamically adjusted with the variation of vehicle velocity which keep the maximum throughput.

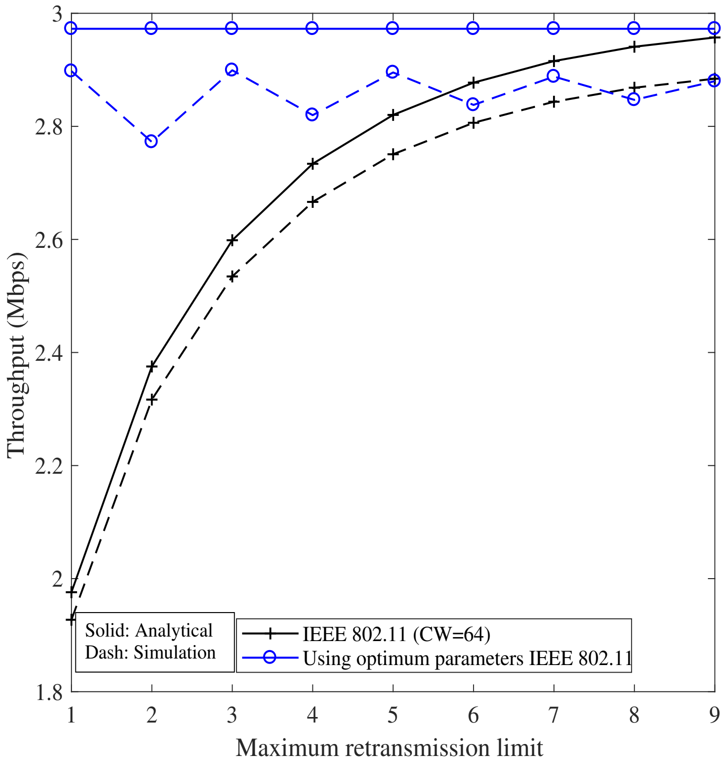

Figure 6.9 Throughput versus maximum retransmission limit

The effect of maximum retransmission limit versus throughput is presented in Figure 6.9. When the number of the maximum retransmission limit increases, the packet transmission after failed transmission increases to have successful transmission and backoff also increases. Throughput will increase with the increase of maximum retransmission limit because the packet will wait more due to higher backoff for collision free transmission. N, CW size, and v are dynamically adjusted with the deviation of m_r which keep the throughput in maximum level.

Optimum parameters variations in 3D is presented in Figure 6.10. Optimum CW size is taken based on the number of vehicles and velocity. With the increase of number of vehicles and the velocity, CW size is increasing to decrease collision probability which will maximize throughput.

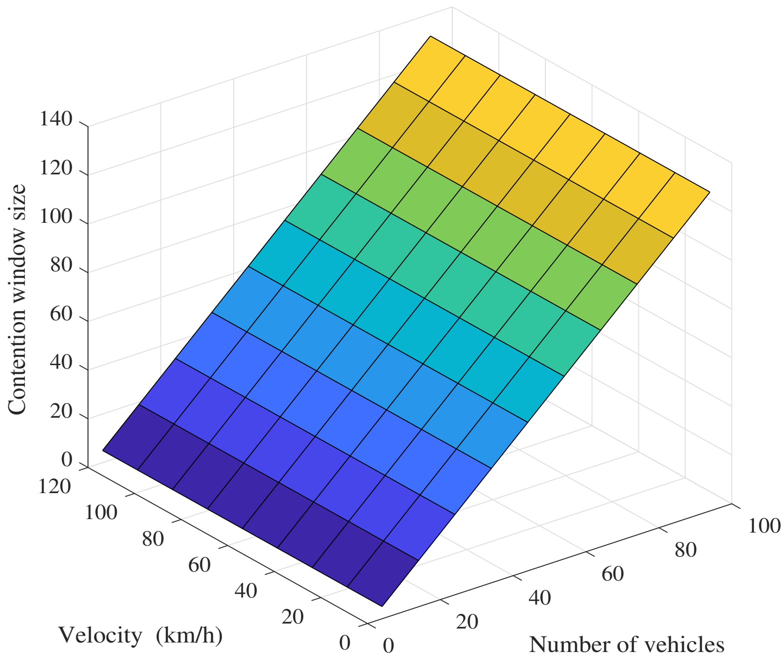

Figure 6.10 Optimum parameters variations in 3D

6.1.3 Optimization of CB-MAC protocol

Though performance of CB-MAC protocol is affected by cluster size, no mechanism is provided to manage cluster size efficiently. Here, performance of CB-MAC protocol is optimized for VANETs by optimizing transmission probability with cluster size. Each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in VANET. Therefore, optimum number of clusters is defined based on the number of vehicles in VANETs. In order to get optimum throughput S, eq. (4.16) can be rearranged as:

$$S_k = \frac{L}{T_s - T_c + \frac{P_b(T_c - T_{slot}) + T_{slot}}{P_s P_b}}. \tag{6.15}$$

Since L, T_s, T_c and T_{slot} are constants, S will be maximum when the following quantity is optimized:

$$\frac{P_s P_b}{P_b + \frac{T_{slot}}{(T_c - T_{slot})}} = \frac{(x-1)P_{t-cl}(1-P_{t-cl})^{x-2}}{\left(1-(1-P_{t-cl})^{x-1}\right)+a} \tag{6.16}$$

where $a = \frac{T_{slot}}{T_c - T_{slot}}$. Taking the derivative of (6.17) with respect to P_{t-cl} and equalizing to 0:

$$a(x-1)P_{t-cl} - a + (1-P_{t-cl})^{x-1} + (x-1)P_{t-cl} - 1 = 0, \tag{6.17}$$

Under the condition P_{t-cl}«1, the following series expansion takes place[30]:

$$(1-P_{t-cl})^{x-1} \approx 1-(x-1)P_{t-cl} + \frac{(x-1)(x-2)P_{t-cl}{}^2}{2}. \tag{6.18}$$

Then eq. (6.18) can be simplified as

$$a(x-1)P_{t-cl} - a + \frac{(x-1)(x-2)P_{t-cl}{}^2}{2} = 0. \tag{6.19}$$

Therefore, optimum P_{t-cl} can be derived as

$$\begin{aligned} P_{t-cl} &= \frac{\sqrt{a(x-1)(a(x-1)+2(x-1)-2)}-a(x-1)}{(x-1)(x-2)} \\ &= \frac{a\sqrt{1+2/a-2/(a(x-1))}-1}{(x-2)}. \end{aligned} \tag{6.20}$$

where $x > 2$. After taking second derivative of (6.15) with respect to P_{t-cl}, we get negative value of P_{t-cl} as

$$P_{t-cl} = -\frac{t}{x-2}, \tag{6.21}$$

which shows it is the maximum P_{t-cl}. To have the maximum S, each vehicle has to transmit with the optimum P_{t-cl}. Therefore, P_{t-cl} should adopt the value of optimum P_{t-cl}. Basically, the optimum S can be achieved by sizing P_{t-cl} in relation to cluster size. From equation (4.3), it is obvious that P_{t-cl} depends on n and j where n is not directly controllable. The only way to have maximum S is to tune j. Now from (4.3) and (6.21), the optimum j can be found as

$$j_{opt} = \left\lceil N\left(1-\frac{a\sqrt{1+2/a-2/(a(x-1))}-1}{(x-2)}\right)\right\rceil \tag{6.22}$$

where $\lceil . \rceil$ denotes ceil operation and $x > 2$.

A packet is dropped if it is failed to transmit until maximum retransmission limit (m_r). Therefore, PDR can be written as

$$PDR = (1-P_s)^{m_r}. \tag{6.23}$$

The optimum PDR can be achieved by getting optimum P_t that can be obtained by using optimum P_{t-cl}.

Average packet delay $E[D]$ can be written as

$$E[D] = T_e\left(N - \frac{P_{drop}}{1-P_{drop}} \times \frac{2}{1+CW+m_r CW/2}\right) \tag{6.24}$$

where P_{drop} and W are probability that a packet will be finally dropped, and contention window size, respectively. The optimum $E[D]$ can be attained by obtaining optimum T_e that can be achieved by using optimum P_{t-cl}.

Performance of optimized CB-MAC protocol is examined and analytical analysis is verified through Monte-Carlo simulations. Table 6.3 provides value of parameters used in the simulation. Simulation results are obtained in SUMO and MATLAB. Firstly, microscopic mobility model is produced in SUMO, then output of SUMO is used as input to MATLAB. Simulation results are obtained by 1000 Monte-Carlo iterations. In the CB-MAC study, parameters related to mobility such as number of vehicles, vehicle velocity, etc. are assumed. On the other hand, in this study practical mobility parameters are taken from SUMO which makes the analysis realistic. Figure 6.11 exhibits the area map and traffic simulation of the area considered in SUMO. The comparison of the CB-MAC, optimized CB-MAC and traditional MAC which is based on IEEE 802.11 is presented. The cluster size is 10 for CB-MAC.

Table 6.3 Parameter values used in simulation

Parameter	Value
$T_{slot}, T_{delay}, T_{SIFS}, T_{DIFS}$ μs	20, 1, 10, 50
L_h, L (bytes)	50, 512
RTS, CTS, ACK (bytes)	26, 20, 14
R_c, R_d, λ (Mbps)	1, 11, 0.5
N, CW	0-50, 64
m_r (sm), m_r (nsd)	2, 7
Maximum vehicle velocity (m/s)	19.81

Figure 6.11 Simulation of Taksim square, Istanbul in SUMO 1.2.0

Figure 6.12 presents throughput against number of vehicles. Throughput is increasing with the increase of the number of vehicles until more packets contending which results in more collisions and degrades the performance. The throughput of optimized

CB-MAC protocol is better than both traditional MAC and CB-MAC protocols. Since clustering limits the channel contention and efficiently controls the network topology, CB-MAC protocol has higher throughput than traditional MAC protocol. P_{t-cl} is maximized with j_{opt} and the throughput is optimized.

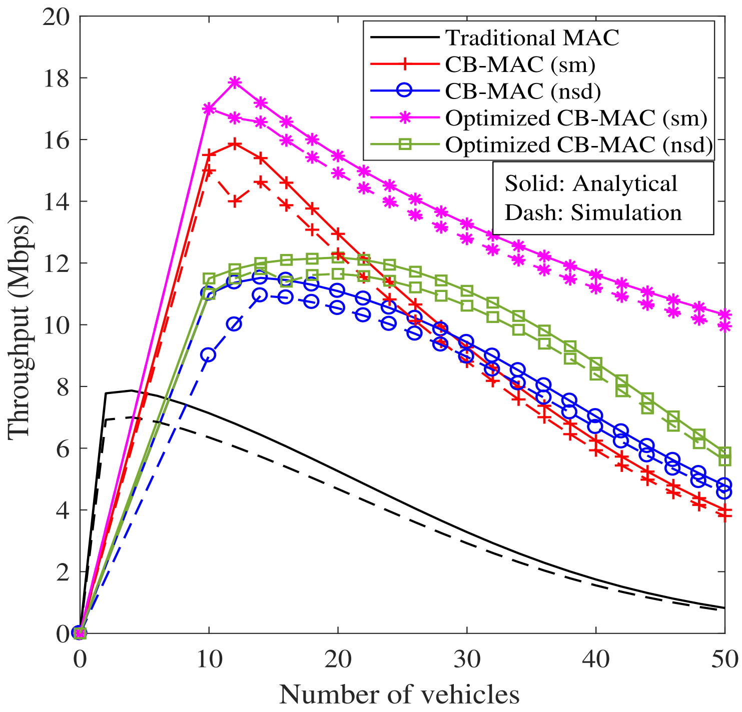

Figure 6.12 Throughput against number of vehicles

Figure 6.13 shows PDR against number of vehicles. PDR rises with the number of vehicles which reduces reliability of transmission. When the number of vehicles is increased, the number of packets contending for the delivery is increased which increases collision as well as PDR. PDR of proposed optimization mechanism is lower than the CB-MAC and traditional MAC protocol. Clustering makes communication stable, CB-MAC protocol has lower PDR than traditional MAC protocol. Since successful transmission probability is optimized by using optimum transmission probability with optimum cluster size, PDR is lower than CB-MAC in optimized CB-MAC which makes communication more reliable.

Figure 6.14 demonstrates average packet delay against number of vehicles. With the increment of number of vehicles, delay increases because probability of channel busy as well as collision increase. The delay for optimized CB-MAC is less than CB-MAC and traditional MAC. Clustering limits the channel contention which reduces the probability of channel busy and collision that decreases the delay. Therefore, CB-MAC has lower delay than traditional MAC. Optimized CB-MAC limits channel contention

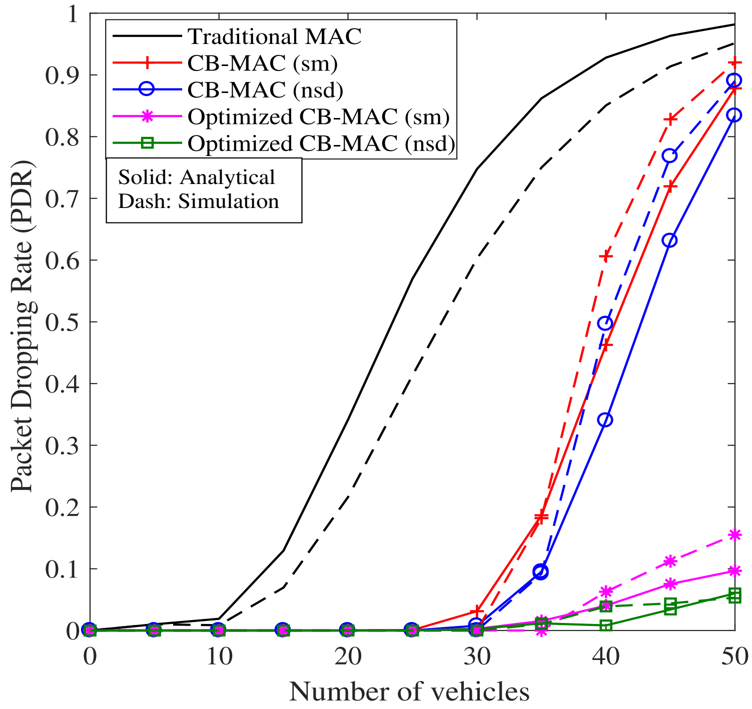

Figure 6.13 PDR against number of vehicles

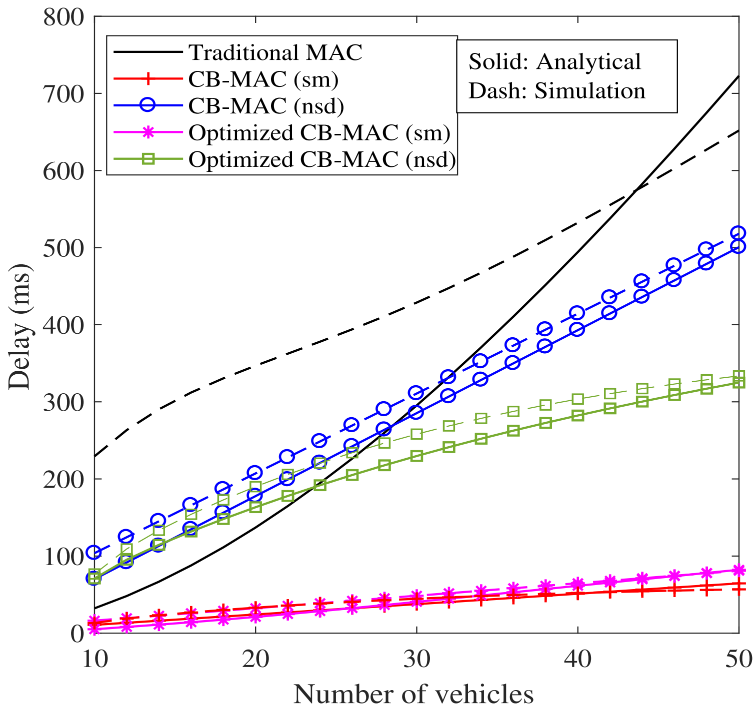

Figure 6.14 Delay versus number of vehicles

more efficiently than CB-MAC protocol by optimizing cluster size which results in lower delay than CB-MAC.

Table 6.4 Optimum number of cluster for different number of vehicles

N	j_{opt}
1-19	1
20-30	2
31-40	3
41-50	4
51-60	5
61-70	6
71-80	7
81-90	8
91-100	9

Table 6.5 Optimum P_{t-cl} and maximum throughput under different number of vehicles for optimized CB-MAC

N	P_{t-cl}	S (sm) Mbps	S (nsd) Mbps
10	0.0298	19	14.0013
20	0.0168	16.5244	14.0929
30	0.0111	13.5433	13.5448
40	0.0083	11.1272	13.0474
50	0.0066	9.5588	12.5934

The analytical analysis supports the simulation results. It is also noticeable that high priority sm has higher throughput and lower delay than nsd. Though CB-MAC protocol fulfills the performance criteria of VANETs, the performance can be optimized by the optimization mechanism. Table 6.4 presents optimum number of cluster under different traffic conditions. To design stable clustering, a range of the number of vehicle is provided. If clusters are formed as Table 6.4, i.e. optimum number of clusters are formed for particular number of vehicles, then the performance will be optimized. Table 6.5 presents the optimum P_{t-cl} and maximum S for both sm and nsd under different number of vehicles. For a particular number of vehicles if each vehicle adopt the optimum transmission probability then optimum throughput is achievable. Designing of VANET clustering to achieve optimum performance is understandable from Table 6.4 and Table 6.5. For example, if 4 clusters are formed for 50 vehicles that adopt optimum P_{t-cl} 0.0066 which achieves maximum throughput 9.5588 Mbps for sm and 12.5934 Mbps for nsd.

6.1.4 Comparison between IEEE 802.11p and IEEE 802.11

In this section, the comparison between IEEE 802.11p and IEEE 802.11 is presented. sm is considered. Parameter values are used as Table 6.1 and Table 6.2, respectively.

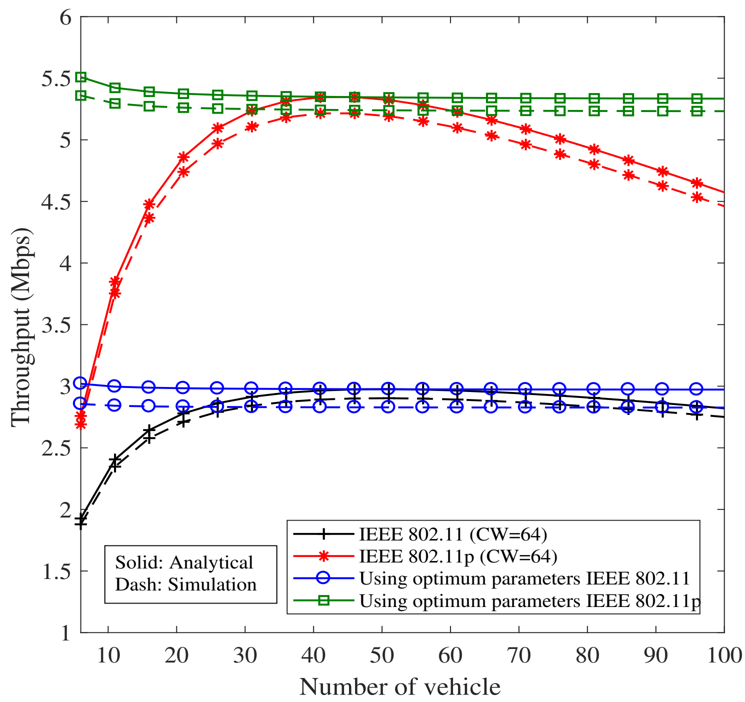

Figure 6.15 Throughput versus number of vehicles

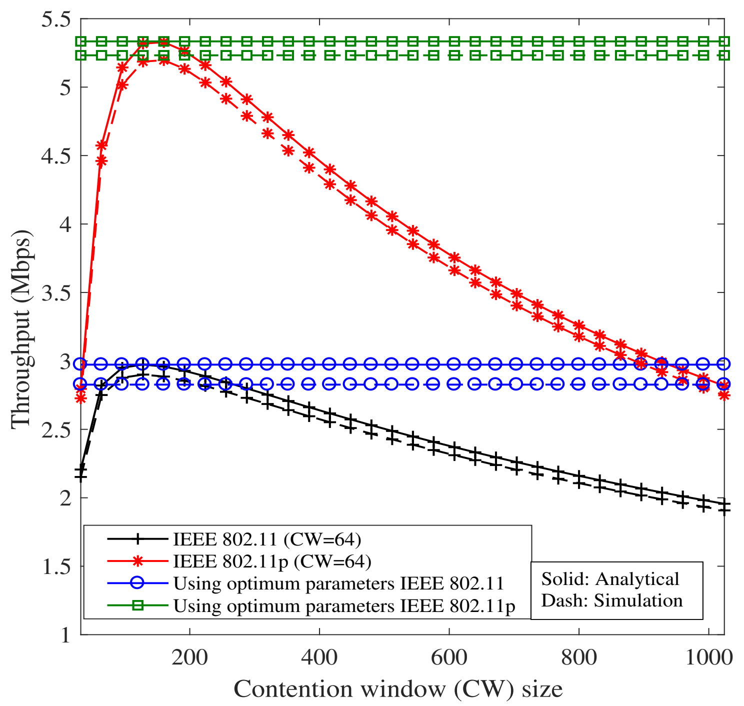

Figure 6.16 Throughput against CW size

Throughput versus number of vehicles, CW size, and velocity are demonstrated in Figure 6.15, 6.16, and 6.17, respectively. Performance of IEEE 802.11p standard is better than 802.11 for safety messages because RTS/CTS mechanism of the IEEE

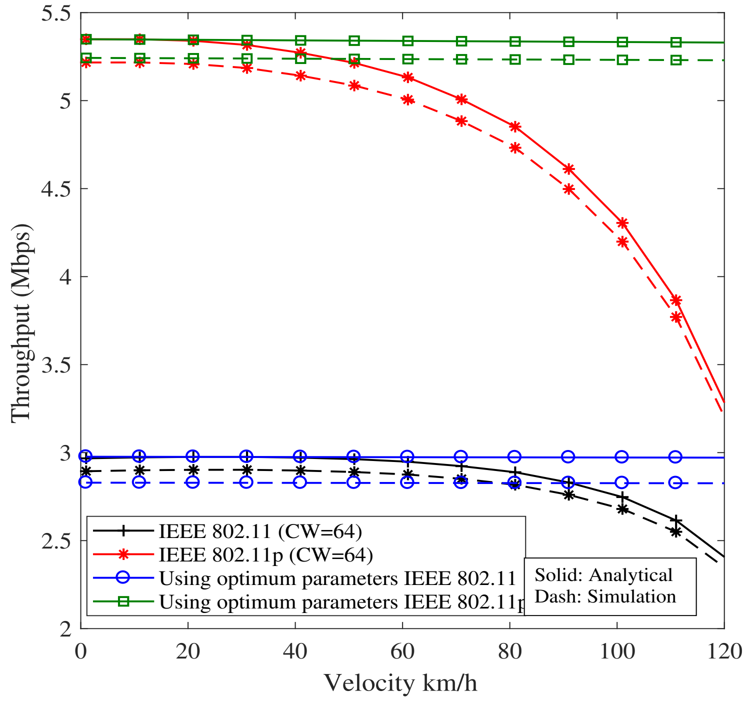

Figure 6.17 Throughput against vehicle velocity

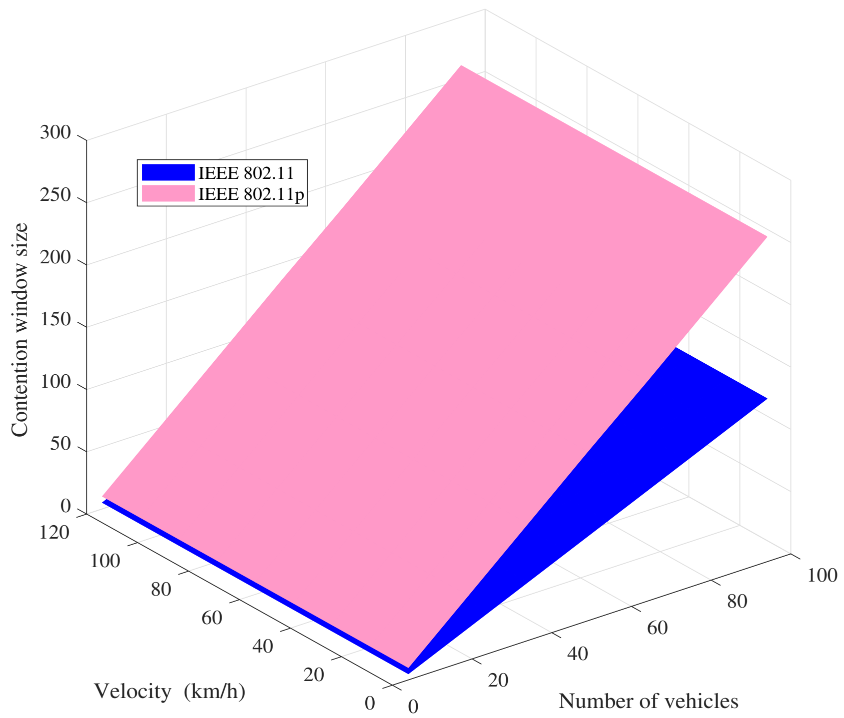

Figure 6.18 Optimum parameters variations for IEEE 802.11 and IEEE 802.11p in 3D

802.11 is inactive in broadcast mode as RTS/CTS mechanism requires CTS after RTS. Thus, when message is broadcast to all vehicles, all vehicles have to send CTS. Hence, simultaneous CTS transmission will cause more collisions.

Optimum parameters variations for IEEE 802.11 and IEEE 802.11p in 3D is presented in Fig. 6.18. CW size is taken based on number of vehicles and vehicle velocity. How CW size is varies according to number of vehicles and vehicle velocity is shown in the figure. From the figure, it can be seen that IEEE 802.11p takes higher CW size than IEEE 802.11 to have optimum performance

It is also noticeable that simulation results support analytical results. Without using optimization mechanism, throughput changes with parameters variation. On the other hand, throughput is always in optimum level while optimum mechanism is used. Since any of the parameters changes, others are taking the optimum value in respect to the altered parameters, throughput achieves the optimum value.

6.2 Complexity Analysis

In this section, complexity analysis of IEEE 802.11p, IEEE 802.11, CB-MAC, and RECV-MAC are presented. The program runs on a computer with core i3 1.70 GHz processor, 4GB RAM and 64 bit operating system. The analysis is conducted in MATLAB.

6.2.1 Complexity analysis of IEEE 802.11p

Elapse time of IEEE 802.11p for each iteration is presented in Table 6.6.

Table 6.6 Elapse time for each iteration

Iteration	Elapse time (seconds)
1	0.004671
2	0.004638
3	0.005354
4	0.005031
5	0.007010
6	0.006674
7	0.006299
8	0.005585
9	0.006151
10	0.005820

The average elapse time is 0.0057233 s. The analysis is done for 50 vehicles. With increase of the number of vehicles (n) time consumption is increasing. The asymptotic computational complexity of CSMA/CA protocol is O(n).

6.2.2 Complexity analysis of IEEE 802.11

Elapse time of IEEE 802.11 for each iteration is presented in Table 6.7.

Table 6.7 Elapse time for each iteration

Iteration	Elapse time (seconds)
1	0.008056
2	0.008292
3	0.015999
4	0.007572
5	0.011058
6	0.013106
7	0.012406
8	0.009716
9	0.018397
10	0.009505

The average elapse time is 0.0114107 s. The analysis is done for 50 vehicles. Time consumption increases with the number of vehicles (n). The asymptotic computational complexity of CSMA/CA protocol is O(n).

6.2.3 Complexity analysis of CB-MAC protocol

Elapse time of CB-MAC protocol for each iteration is given in Table 6.8.

Table 6.8 Elapse time for each iteration

Iteration	Elapse time (seconds)
1	0.024747
2	0.028110
3	0.019896
4	0.020632
5	0.024794
6	0.021133
7	0.019557
8	0.019517
9	0.020890
10	0.020778

The average elapse time is 0.0220064 s. The analysis is done for 50 vehicles. With increase of the number of vehicles (n) time consumption is increasing. The asymptotic computational complexity of CB-MAC protocol is O(n).

6.2.4 Complexity analysis of RECV-MAC protocol

Elapse time of RECV-MAC protocol for each iteration is given in Table 6.9.

Table 6.9 Elapse time for each iteration

Iteration	Elapse time (seconds)
1	0.026384
2	0.015430
3	0.018011
4	0.016028
5	0.016657
6	0.016271
7	0.099065
8	0.013392
9	0.015907
10	0.015484

The average elapse time is 0.0252629 s. The analysis is done for 100 vehicles. Time consumption depends on the number of vehicles. Since time consumption is increasing with the number of vehicles (n) linearly, the asymptotic computational complexity of RECV-MAC protocol is O(n).

6.2.5 Comparison of Complexity Analysis

In this section, comparison of complexity analysis is presented. CB-MAC protocol has lower complexity than IEEE 802.11 because clustering limits channel contention and sm does not use any RTS/CTS exchange before data transmission. RECV-MAC protocol has higher complexity than IEEE 802.11p because cooperative communication initiates complexity.

7
Results And Discussion

7.1 Conclusion

IEEE 802.11p defined PHY and MAC layers layer specifications for VANETs. DCF is the basic access method and EDCAF is designed to support QoS. An analytical model is presented to examine the performance of IEEE 802.11p DCF as well as EDCAF in VANETs for both sm and nsd. The theoretical model is carried out based on Markov chain model. All key parameters that can influence the performance of IEEE 802.11p MAC for VANETs such as number of vehicles, velocity, vehicle density, contention window (CW) size etc. are taken into account. The association among performance metrics and the IEEE 802.11p MAC parameters are determined. Channel busy probability, probability of collision, probability of successful transmission, throughput, and delay expressions are derived. Numerical results are demonstrated to scrutinize the impact of IEEE 802.11p MAC for VANETs and whether IEEE 802.11p can fulfill the performance criteria for VANETs or not is checked. Firstly, ideal channel condition is assumed. Later, the effect of capture and channel fading is studied. Nakagami, Rayleigh, and Rician faded channels are considered. The probability of successful and unsuccessful transmission, probability of frame capture, outage probability, Bit error rate (BER), throughput, and delay expressions are obtained. Throughput with capture is always greater than throughput without capture due to increase of successful transmission probability. On the other hand, if the probability of errored frame increases, throughput decreases due to increase of unsuccessful transmission probability. Obviously, the throughput of safety messages is always greater than the non-safety data. On the other hand, the delay of safety messages is always lower than non-safety data.

Later IEEE 802.11 incorporated IEEE 802.11p. The performance of the IEEE 802.11 DCF as well as EDCAF for both sm and nsd is scrutinized. Markov chain model based analytical model is developed where all key parameters that can affect the performance are taken into consideration. The relationship among performance metrics and MAC parameters are achieved. The probability of collision, probability of successful transmission, throughput, PDR, and delay expressions are derived. Numerical results are presented to investigate the performance of IEEE 802.11 MAC for VANETs and whether the IEEE 802.11 can fulfill the performance criteria for VANETs or not is checked. At first, we considered ideal channel and later channel fading and capture effect is taken into study. However, both IEEE 802.11p and IEEE 802.11 MAC can not fulfils the strict delay constraint of 100 ms for sm.

High mobility and relative mobility among the vehicles cause dynamic topology changes and frequent link breakage which cause unstable communication. Cluster-based communication can improve the reliability of communication by forming a cluster with adjacent vehicles moving in the same direction. In this thesis, a novel cluster-based MAC (CB-MAC) protocol based on IEEE 802.11 is proposed both for safety messages and non-safety data. The FSM of the CB-MAC protocol is given. The mechanism of cluster formation and CH election is described. In order to maximize the throughput, a cluster is formed by grouping nearby vehicles driving in the same direction. The process of joining and leaving a cluster has been defined and cluster merging process is provided. Furthermore, to ensure cluster-based communication, existing control packets format are modified and new control packets are introduced. Since RTS/ CTS mechanism of the IEEE 802.11 is inoperative in broadcast mode, the RTS/CTS mechanism is not used for sm. In contrast, the RTS/CTS mechanism is used for nsd transmission to mitigate the hidden node problem. An analytical model based on Markov chain model has been derived. Numerical results illustrate that the CB-MAC protocol provides a significant improvement in the performance. CB-MAC protocol maximizes the throughput and ensures reliability by reducing the PDR. Moreover, CB-MAC protocol fulfills the strict delay requirement of 100 ms for sm. Clustering initializes the progress of overall system performance by minimizing the effect of high mobility, limiting channel contention and simplifying handover. CB-MAC protocol avoids hidden node problem by using RTS and CTS as well as ensures maximum resource utilization. Extensive performance analysis of CB-MAC protocol includes future research works. We shall consider channel fading and capture effect in future studies.

Alternatively, cooperative transmission can improve the communication reliability and can enhance communication rate with lower delay by alleviating wireless channel impairments caused by the mobility in VANETs. In this thesis, a novel reliable and efficient cooperative MAC protocol for VANETs is proposed, referred to as RECV-MAC. The RECV-MAC protocol was designed to support both safety messages and non-safety data transmission. Since a random access mechanism is the most suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. CSMA/CA which is used by the IEEE 802.11p. Therefore, the proposed

RECV-MAC protocol is compatible with the IEEE 802.11p. New control messages were introduced to ensure effective cooperative communication. An algorithm was proposed for selecting suitable data transmission mode. Optimal helper selection mechanism was also described. We presented an analytical analysis of the RECV-MAC protocol which is based on Markov chain model. The parameters that could impact performance were taken into consideration. Mobility and overhead introduced by cooperative communication were considered. The relationship among parameters and performance metrics were derived. Network performance measures such as system throughput, collision probability, successful transmission probability, PDR, and delay were derived. We assessed the performance of the RECV-MAC protocol through numerical analysis. Numerical results reveal that the RECV-MAC protocol provides noteworthy enhancement in system throughput and also satisfies 100 ms strict delay requirement of safety messages in VANETs. Furthermore, the reliability of the communication is increased by decreasing PDR. RECV-MAC protocol achieved the stated objectives. Extensive performance analysis of RECV-MAC protocol includes future research works. We shall consider non-saturated condition, different vehicle density or traffic scenarios etc. The effect of channel fading and capture will be studied too.

Throughput of IEEE 802.11p and IEEE 802.11 is optimized for safety messages in VANETs. The optimum throughput is achieved by dynamically setting parameters such as the number of vehicles, CW size, maximum retransmission limit, and vehicle velocity when any of these parameters varies. Markov chain model based analytical study is presented. Optimum number of vehicles, CW size, maximum retransmission limit, and vehicle velocity expressions are derived. The comparison between IEEE 802.11 and IEEE 802.11p for safety messages in VANETs is provided. Throughput is optimized for both IEEE 802.11 and 80211p standard. The microscopic mobility model is generated in SUMO. Performance of optimization mechanism is examined and analytical analysis is verified through Monte-Carlo simulations. Simulation results depict that the performance of proposed scheme is always better than both IEEE 802.11 and 802.11p.

Performance of CB-MAC protocol is optimized by optimizing transmission probability with cluster size for both for sm and nsd. To achieve optimized performance each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in the VANET. Therefore, optimum number of clusters is defined based on the number of vehicles in VANETs. An analytical study based on Markov chain model is provided. Optimum probability of transmission, optimum number of clusters expressions are obtained. Simulation results are presented which support and verify analytical analysis. The microscopic mobility model is generated in SUMO. Optimum number of clusters for different number of vehicles is presented. Moreover, optimum transmission probability and maximum throughput for different number of vehicles is provided. It is obvious that the optimization mechanism improves performance of the CB-MAC protocol by increasing throughput and decreasing delay and PDR. Therefore, optimized CB-MAC protocol improves communication quality and increases the reliability of communication.

Complexity analysis is presented. Since clustering limits channel contention and CB-MAC protocol does not use RTS/CTS exchange in sm, CB-MAC protocol has lower complexity thank IEEE 802.11. On the other side, RECV-MAC protocol has higher complexity than IEEE 802.11p because cooperative communication initiates complexity.

7.2 Future Works

Extensive performance analysis of CB-MAC and RECV-MAC protocols includes future research works. The non-saturated condition different vehicle density or traffic scenarios etc. will be considered. Moreover, only ideal channel condition is considered in the analysis of CB-MAC and RECV-MAC protocols. In future study, channel fading and capture effect will be considered. Though CB-MAC and RECV-MAC protocols perform better than existing schemes and fulfill performance criteria for safety messages in VANETs, the performance of CB-MAC and RECV-*MAC protocols degrade in high traffic scenarios. Performance optimization of CB-MAC and RECV-MAC protocols will be studied in future work too.

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Publications From the Thesis

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Papers

1. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “CB-MAC: A novel cluster-based MAC protocol for VANETs,” in IET Intelligent transport systems, vol. 13, no. 4, pp. 587-595, 2019. (DOI: 10.1049/iet-its.2018.5267)

2. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “RECV-MAC: A novel reliable and efficient cooperative MAC protocol for VANETs,” in IET Communications, vol. 13, no. 16, pp. 2541-2549, 2019. (DOI: 10.1049/iet-com.2018.6171)

3. A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, “Performance optimization of CB-MAC protocol for VANETs,” under review in IEEE Wireless communications letters, 2020.

4. A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, “Optimization of throughput for safety messages in VANETs,” under review in IEEE Wireless communications letters, 2020.

5. A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, “Performance of the IEEE 802.11p MAC under channel fading and capture effect in VANETs,” under review in IEEE Transactions on vehicular technology, 2020.

Conference Papers

1. A. F. M. Shahen Shah, H. Ilhan and U. Tureli, "Performance and complexity analysis of MAC protocol for VANETs," in Proc. of IEEE 10th Annual information technology, electronics and mobile communication conference (IEMCON), Vancouver, BC, Canada, October, 2019, pp. 1081-1086. (DOI: 10.1109/IEMCON.2019.8936150)

2. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “Modeling and performance analysis of the IEEE 802.11 MAC for VANETs under capture effect,” in Proc. of IEEE 20th Wireless and microwave technology conference (WAMICON), Cocoa Beach, Florida, USA, April, 2019, pp. 1 - 5. (DOI: 10.1109/WAMICON.2019.8765446)

3. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “Modeling and performance analysis of the IEEE 802.11p MAC for VANETs,” in Proc.

of IEEE 42st International conference on telecommunications and signal processing (TSP), Budapest, Hungary, July, 2019, pp. 393-396. (DOI: 10.1109/TSP.2019.8769073)

4. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “Modeling and performance analysis of the IEEE 802.11 MAC for VANETs under channel fading and capture effect,” in Proc. of IEEE International symposium on innovations in intelligent systems and applications (INISTA), Sofia, Bulgaria, July, 2019, pp. 1 - 5. (DOI: 10.1109/INISTA.2019.8778288)

5. Muhammet Ali Karabulut, A. F. M. Shahen Shah and Haci Ilhan, "Performance modeling and analysis of the IEEE 802.11 DCF for VANETs," ,” in Proc. of IEEE 9th International congress on ultra modern telecommunications and control systems and workshops (ICUMT), Munich, 2017, pp. 346-351. (DOI: 10.1109/ICUMT.2017.8255147)

Books/ Book chapters

1. A. F. M. Shahen Shah, Muhammet Ali Karabulut, and Haci Ilhan, “Performance modeling and analysis of the IEEE 802.11 EDCAF for VANETs,” In: Arai K., Kapoor S., Bhatia R. (eds): Advances in intelligent systems and computing, vol 869. Springer, Cham, 2019, pp. 34-46. (DOI: 10.1007/978-3-030-01057-7-3)

2. A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, “qCB-MAC: QoS aware cluster-based MAC protocol for VANETs,” In: Arai K., Kapoor S., Bhatia R. (eds): Advances in intelligent systems and computing, vol 857. Springer, Cham, 2019, pp. 685-695. (DOI: 10.1007/978-3-030-01177-2-50)

Projects

1. “New cooperative MAC protocols for VANETs” Funded by Scientific Research Projects of Yildiz Technical University (2018 - continued) Position: Researcher

2. “An efficient and reliable cooperative MAC protocol for mobility aware cluster-based VANETs” Funded by the Scientific and Technological Research Council of Turkey (TUBITAK) (2019 - continued) Position: Scholar

Sl No	Title	Research Output
	Papers	
1	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "CB-MAC: A novel cluster-based MAC protocol for VANETs," in IET Intelligent transport systems, vol. 13, no. 4, pp. 587-595, 2019.	Due to relative mobility, topology changes rapidly with frequent link breakage in vehicular ad hoc networks (VANETs). Clustering VANETs into small groups limits channel contention and controls the network topology efficiently. In this paper, a novel cluster-based MAC (CB-MAC) protocol is proposed for VANETs. The cluster formation process is defined. Moreover, cluster head (CH) election and cluster merging processes are described for efficient communication in the cluster as well as out of the cluster. The mechanism defined in IEEE 802.11 standard is specially designed for only direct communications and is not suitable for cluster-based communications. Therefore, new control packets are introduced and the existing control packet format is modified to support cluster-based communications. For effective MAC protocol design, the request to send (RTS)/ clear to send (CTS) mechanism is not used for safety messages which are of broadcast nature. On the other hand, the RTS/CTS mechanism is used for non-safety data delivery to eliminate hidden node problem. Markov chain model based analytical model is presented to explore the performance of proposed CB-MAC protocol. The proposed protocol is validated by numerical studies. The numerical results exhibit that the proposed CB-MAC protocol improves system performance and satisfies the delay constraint of 100 ms for safety messages.

2	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "RECV-MAC: A novel reliable and efficient cooperative MAC protocol for VANETs," in IET Communications, vol. 13, no. 16, pp. 2541-2549, 2019.	In vehicular ad hoc networks (VANETs), mobility among vehicles can result in rapid topology changes with frequent link breakage and unstable communications, which cause collision and packet loss. Conversely, cooperative transmission can improve communication reliability and can enhance communication rate with lower delay by alleviating wireless channel impairments caused by mobility in VANETs. In this study, a novel reliable and efficient cooperative medium access control protocol for VANETs (RECV-MAC) is proposed. Since a random access mechanism is suitable and efficient because of the dynamic and open nature of VANETs, authors used the random access approach, i.e. carrier sense multiple access with collision avoidance, which is used by IEEE 802.11p. Therefore, RECV-MAC protocol is compatible with IEEE 802.11p. New control messages are introduced to support cooperative communication. The mechanism is defined to choose suitable transmission mode as well as to select optimal helper. To investigate the performance of RECV-MAC protocol, Markov chain model-based analytical analysis is provided. The RECV-MAC protocol is validated by numerical results which demonstrate that RECV-MAC protocol improves the performance with higher throughput, enhances the reliability of communication by decreasing packet dropping rate (PDR), and decreases delay, in particular, satisfies the delay constraint of 100 ms for sm.

3	A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, "Performance optimization of CB-MAC protocol for VANETs," under review in IEEE Wireless communications letters, 2020.	Though performance of CB-MAC protocol is affected by cluster size, no mechanism is provided to manage cluster size efficiently. In this letter, performance of CB-MAC protocol is optimized for VANETs by optimizing transmission probability with cluster size. Each vehicle should adopt the optimum transmission probability in the cluster which can be obtained by tuning the number of clusters in VANET. Therefore, optimum number of clusters is defined based on the number of vehicles in VANETs. An analytical study based on Markov chain model is provided. Optimum transmission probability, and optimum number of clusters expressions are derived. The microscopic mobility model is generated in SUMO for practical scenario. Simulation results are presented which verify analytical (theoretical) analysis and show that performance of CB-MAC protocol is maximized.
4	A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, "Optimization of throughput for safety messages in VANETs," under review in IEEE Wireless communications letters, 2020.	In VANETs, throughput changes with the variation of traffic, contention window (CW) size, retransmission limit, and vehicle velocity. If any of these parameters is changed, throughput changes and even throughput may become negligible. In this letter, throughput is optimized for prime important safety messages in VANETs. If any of these parameters changes, other parameters will be dynamically adjusted to keep throughput in maximum level. The comparison between IEEE 802.11 and IEEE 802.11p for safety messages in VANETs is presented as well as throughput is maximized for both IEEE 802.11 and IEEE 802.11p. Markov chain based analytical model is developed and optimum expressions are derived. The microscopic mobility model is generated in SUMO. Monte Carlo simulation results are presented which verify analytical analysis and show that throughput is always in maximum level regardless of parameters variation.

5	A. F. M. Shahen Shah, Muhammet Ali Karabulut, Haci Ilhan and Ufuk Tureli, “Performance of the IEEE 802.11p MAC under channel fading and capture effect in VANETs,” under review in IEEE Transactions on vehicular technology, 2020.	Two major factors which influence the performance of VANETs in practical transmission are bit error and channel capture. Previous works investigated these effects separately. In this paper, we present a comprehensive analysis that integrates the two important factors. To assess the performance of the IEEE 802.11p medium access control (MAC) for VANETs under channel fading and capture effect, an analytical model based on Markov chain model is presented. The parameters that could impact performance are studied. The relationship among parameters and performance metrics are derived. All faded channels such as Nakagami, Rayleigh, and Rician faded channels are considered. The probability of successful and unsuccessful transmission, probability of frame capture, outage probability, Bit error rate (BER), throughput, and delay expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented.
	Conference papers	
1	A. F. M. Shahen Shah, H. Ilhan and U. Tureli, "Performance and complexity analysis of MAC protocol for VANETs," in Proc. of IEEE 10th Annual information technology, electronics and mobile communication conference (IEMCON), Vancouver, BC, Canada, October, 2019, pp. 1081-1086.	In this paper, to assess the performance of the IEEE 802.11 medium access control (MAC) for VANETs, an analytical model based on Markov chain model is presented. Both sm and nsd are considered. The parameters that could impact performance such as number of vehicles, velocity, vehicle density, contention window (CW) size, packet size, transmission range etc. are considered. The relationship among parameters and performance metrics are derived. Ideal channel condition is considered. The probability of successful transmission, throughput, and delay expressions are obtained. Complexity analysis is presented. Furthermore, to verify the analytical studies numerical results are demonstrated and whether the IEEE 802.11 can fulfill the performance criteria for VANETs or not is checked.

2	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "Modeling and performance analysis of the IEEE 802.11 MAC for VANETs under Capture Effect," in Proc. of IEEE 20th Wireless and microwave technology conference (WAMICON), Cocoa Beach, Florida, USA, April, 2019, pp. 1-5.	Channel capture influences the performance of VANETs in practical transmission. In this paper, to assess the performance of the IEEE 802.11 medium access control (MAC) for VANETs under capture effect, an analytical model based on Markov chain model is presented. The parameters that could impact performance are studied. The relationship among parameters and performance metrics are derived. The probability of successful transmission, probability of frame capture, and throughput expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented.
3	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "Modeling and performance analysis of the IEEE 802.11p MAC for VANETs," in Proc. of IEEE 42st International conference on telecommunications and signal processing (TSP), Budapest, Hungary, July, 2019, pp. 393-396.	In this paper, to assess the performance of the IEEE 802.11p medium access control (MAC) for VANETs, an analytical model based on Markov chain model is presented. The parameters that could impact performance such as number of vehicles, velocity, vehicle density, contention window (CW) size, packet size, transmission range etc. are taken into consideration. The relationship among parameters and performance metrics are derived. The probability of successful transmission, throughput, and delay expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented and whether the IEEE 802.11p can fulfill the performance criteria for VANETs or not is checked.
4	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "Modeling and performance analysis of the IEEE 802.11 MAC for VANETs under channel fading and capture effect," in Proc. of IEEE International symposium on innovations in intelligent systems and applications (INISTA), Sofia, Bulgaria, July, 2019, pp. 1 - 5.	Two major factors which influence the performance of VANETs in practical transmission are bit error and channel capture. In this paper, to assess the performance of the IEEE 802.11 medium access control (MAC) for VANETs under channel fading and capture effect, an analytical model based on Markov chain model is presented. The parameters that could impact performance are studied. The relationship among parameters and performance metrics are derived. Only Rayleigh faded channels is considered. The probability of successful and unsuccessful transmission, probability of frame capture, and throughput expressions are obtained. Furthermore, to verify the analytical studies numerical results are presented.

5	Muhammet Ali Karabulut, A. F. M. Shahen Shah and Haci Ilhan, "Performance modeling and analysis of the IEEE 802.11 DCF for VANETs," in Proc. of IEEE 9th International congress on ultra modern telecommunications and control systems and workshops (ICUMT), Munich, 2017, pp. 346-351.	In this paper, an analytical model is developed to assess the performance of the IEEE 802.11 distributed coordination function (DCF) for vehicular ad hoc networks (VANETs). Markov chain model based analytical analysis is provided. The correlation between the performance metrics and contention window is derived. Ideal channel condition is considered. Only non-safety data is considered which is unicast mode. Throughput, packet dropping rate (PDR) and delay expressions are obtained. Moreover, numerical results are exhibited to explore the performance of the IEEE 802.11 DCF under different mobility condition for VANETs.
Books / Book chapter		
1	A. F. M. Shahen Shah, Muhammet Ali Karabulut, and Haci Ilhan, "Performance modeling and analysis of the IEEE 802.11 EDCAF for VANETs," In: Arai K., Kapoor S., Bhatia R. (eds): Advances in intelligent systems and computing, vol 869. Springer, Cham, 2019, pp. 34-46.	The IEEE 802.11 standard outlines the specification of medium access control (MAC) and physical layer (PHY) of VANETs which uses the enhanced distributed channel access function (EDCAF) to support contention-based prioritized quality of service (QoS) in the MAC layer. In this paper, an analytical model is developed to estimate the performance of the IEEE 802.11 EDCAF for VANETs. Mobility is taken into consideration. The relationship between performance metrics and EDCAF parameters are derived. Markov chain model based theoretical analysis is carried out. Throughput, packet dropping rate (PDR) and delay terms are attained. Furthermore, the performance model is tested by simulation results.
2	A. F. M. Shahen Shah, Haci Ilhan and Ufuk Tureli, "qCB-MAC: QoS aware cluster-based MAC protocol for VANETs," In: Arai K., Kapoor S., Bhatia R. (eds): Advances in intelligent systems and computing, vol 857. Springer, Cham, 2019, pp. 685-695.	In this paper, a QoS aware cluster-based MAC (qCB-MAC) protocol for VANETs is proposed. The cluster formation mechanism is defined. New control packets are introduced and existing control packets are modified to support cluster based communications. Channel access mechanism is based on the IEEE 802.11 EDCA mechanism for different access categories (ACs) to ensure desired QoS at the MAC layer. Markov chain model based analytical analysis is presented to explore the performance of the proposed MAC protocol. Moreover, numerical results are presented to verify the performance of the proposed qCB-MAC protocol for different ACs. The proposed qCB-MAC protocol improves the system throughput and ensures desired QoS.