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A NEW MEDIA ACCESS CONTROL PROTOCOL FOR VANET: PRIORITY R-ALOHA (PR-ALOHA)

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A NEW MEDIA ACCESS CONTROL PROTOCOL FOR VANET: PRIORITY R-ALOHA (PR-ALOHA)

A DISSERTATION APPROVED FOR THE
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

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Dedication

I dedicate this work to my husband Imad and to my sons Mohammad, Baraa, Zaid, and Laith and to my daughter Lujayn. Thank you for helping me and supporting me throughout my study.

Acknowledgments

First of all, I would like to express my deepest gratitude to my advisor, Dr. Hazem Refai, for his kindness, support, advice, guidance and encouragement during the stages of this research. Many thanks go to my PhD committee members for their support and recommendations. I would like to thank Dr. Tang for spending the time with me discussing papers and simulations.

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From the bottom of my heart I would like to thank my children who always kept encouraging me and telling me: don't stop don't give up. Finally and for most, I would like to thank my husband for all his love, support and believing in me. Most of all, thank you for being there for me all these years, encouraging me to achieve my dreams. I love you honey and dedicate this work to you and to our beautiful children.

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Abstract

More practical applications of Media Access Control (MAC) protocols arise as the world turns increasingly wireless. Low delay, high throughput and reliable communication are essential requirements for standard performance in safety applications (e.g., lane changes warning, pre-crash warning and electronic brake lights). In particular, multi-priority protocols are important in Vehicular Ad Hoc Networks (VANETs), specifically in Inter-Vehicle Communication (IVC) where safety messages are given higher priority and transmitted faster than normal messages. The R-ALOHA protocol is considered one of the few promising protocols for VANETs because it is simple to implement and suitable for medium access control in Ad Hoc wireless networks. However, R-ALOHA lacks the property of prioritizing the different messages. In this dissertation, a new two-level priority MAC protocol called Priority R-ALOHA (PR-ALOHA) is presented to overcome the lack of priority problem in R-ALOHA. The two levels are low priority and high priority where priority is introduced by reserving specific time slots in the frame exclusively for high priority messages. This effectively increases the number of slots that a high priority message may compete for and thus decreases its delay. A two-dimensional Markov model coupled with Monte Carlo simulation is introduced to investigate the dynamic behavior of PR-ALOHA in steady and transient states. Modeling and simulation results of PR-ALOHA show that PR-ALOHA improves the performance of high priority traffic with limited effect on normal network traffic. Then, a dynamic slot allocation algorithm is introduced to PR-ALOH to optimize slot usage. Finally, a mobility model is introduced to emulate the behavior of the vehicles on the road where the performance of the PR-ALOHA with

variable parameters, such as the length of the highway, the vehicle transmission range and the number of vehicles on the road have been investigated. Based on the findings of this dissertation, PR-ALOHA combined with dynamic slot allocation and mobility has a potential in applications like IVC where it can prevent car accidents through faster channel access and rapid transfer of warning messages to surrounding vehicles.

CHAPTER

1. INTRODUCTION

A transportation system is considered to be an important part of our daily life. When traffic congestions or accidents occur they cause extra delays and possible life losses to the vehicle occupants. Vehicle accidents are responsible for an average of 40,000 fatalities per year in each of the USA and Europe [1, 2]. Vehicle to Vehicle (V2V) communication systems are considered to be a promising solution for improving traffic safety, reducing congestion and increasing environmental efficiency of the transportation systems. V2V technology has been developed as part of the Vehicle Infrastructure Integration (VII) initiative [3]. The technology uses 5.8 gigahertz (GHz) frequency band set aside exclusively for transportation-related communications between vehicles, and with road side units (RSU), by the Federal Communication Commission (FCC) considering a transmission range of up to1000 meters [4, 5].

The V2V technologies enable a number of applications ranging from real time communications for safety-critical application, such as systems for early warning of accidents and traffic information systems, to comfort and convenience applications such as traveler information systems. A review of the primary VANET applications is provided in [6]. Some of the applications of V2V include toll collection, red light duration broadcast at traffic lights, transferring maps at hot spots, routing information on traffic jams, and active accident warnings where warning messages are transmitted from cars in the traffic jam to the oncoming cars. Each one of these applications has a certain requirement, but they all share a set of common requirements including a coverage range of 10 to 1000 meters and a latency range between 50 ms to 500 ms with a maximum of 200 ms for safety applications [7]. The main targeted application in our work is safety applications.

To satisfy these applications, new protocols with priority are required. Adding priority to the Reservation ALOHA (R-ALOHA) scheme may provide such a solution. Other protocols have arisen to compete with the ALOHA based algorithms to solve the single channel multi-access problem. To date, the CSMA/CA protocol has been widely used for this purpose by employing an inter frame spacing (IFS) for priority service, i.e. nodes ready for packet transmissions are required to wait for an IFS amount of time, where shorter IFS are used to gain faster access to the radio channel. However, sensing and collision avoidance mechanisms make CSMA/CA unsuitable for delay-sensitive applications, i.e. congested scenarios with high traffic. CSMA and ALOHA are traditional opposing models for multi-access broadcast environments. CSMA has focused on the priority problem through back-off times but lacks the power of reservation scheme produced by R-ALOHA. On the other hand, R-ALOHA has lacked the crucial prioritization absolutely necessary in modern application. To deal with the inefficiency of the binary exponential back-off mechanism in CSMA/CA protocol and the lack of prioritization in ALOHA, this work introduces a new back-off scheme for CSMA/CA and a new Priority R-ALOHA protocol (PR-ALOHA).

The main research objective for the work presented in this dissertation is to introduce a new MAC protocol with two-level priority for R-ALOHA that includes high and low priority which can be used to improve the performance of high priority messages by granting them faster channel access with minimal effect on the low priority/normal priority network messages. This protocol could be useful in applications such as IVC where car accidents could be prevented and human lives could be saved.

The research contributions of this work are summarized as follow:

1. A Two dimensional mathematical Markov model is introduced for the new proposed back-off scheme of CSMA/CA that modifies the Distributed Coordination Function (DCF) implementation specified by the IEEE 802.11 standard and reduce the contention window to half its size after successful transmissions.
2. Simulation analyses of the new back-off scheme are performed to show throughput improvements under ideal and non-ideal channel with channel-induced errors and capture effect.
3. A new ALOHA based MAC protocol with two-level priority called PR-ALOHA is introduced.
4. Inter-vehicle computer communication simulation is performed to test the PR-ALOHA protocol in steady state and evaluate its performance including throughput, delay, packet drop rate and packet delivery rate for each priority level. Communication error and capture effects are considered in the simulations.

5. Dynamic Slot Allocation model is introduced for allocating high priority slots based on the available traffic.
6. Simulation analysis of the Dynamic Slot Allocation is provided where the number of high priority slots is dynamically varied based on the available traffic. As traffic increases the probability of high priority messages increases, but beyond a certain threshold as the traffic increases, the number of high priority slots can be limited or decreased by dynamic PR-ALOHA in order to give low priority traffic higher chances of transmitting.
7. Mathematical discrete Markov chain modeling of the PR-ALOHA is introduced to analytically evaluate the dynamic behavior of the PR-ALOHA protocol. Both distribution and mean of the system stabilization time (SST) and the average number of successful terminals in transient state are evaluated.
8. Monte Carlo simulation of the Markov chain model is performed and the results are compared with the analytical model.
9. A mobility model is introduced to emulate the behavior of the vehicles on the road where different scenarios have been chosen to evaluate the PR-ALOHA protocol with variable parameters, such as the length of the highway, the vehicle transmission range and the number of vehicles on the road.
10. Monte Carlo simulation of the mobility model is performed and the results are presented.

The organization of this dissertation is as follows: We first provide a background in Chapter 2. In Chapter 3, we introduce the Markov model and simulations of the new proposed back-off scheme for the CSMA/CA. In Chapter 4, we describe in detail how the PR-ALOHA protocol works. In Chapter 5, Dynamic Slot Allocation model is introduced. In Chapter 6, simulation results coupled with Markov modeling of the PR-ALOHA are presented. In Chapter 7, mobility model combined with simulation is described. Finally, the conclusions and future research are presented in Chapter 8. Some of the material presented in this dissertation has been presented in our prior publications [8-11].

CHAPTER

2. BACKGROUND

2.1 VANET

V2V communications are also called Car to Car (C2C) communications and sometimes also called Inter Vehicle Communication (IVC). The communication between vehicles is achieved by direct transmission of information between vehicles without the use of a fixed infrastructure. Therefore, IVC networks are considered as mobile ad hoc networks and sometimes referred to as vehicular ad hoc networks (VANETs). The performance of VANETs has been studied both analytically and by simulation [12-19]. VANETs applications are categorized into three categories: safety, convenience, and commercial applications. Safety applications [20, 21] are designed to increase the safety of the driver and the passengers by disseminating information about an important event surrounding the sender vehicle, such as: forward collisions, alternative route warnings, and warning messages about dangerous traffic situations (accident, oil stain, and icy road). In a safety application, the messages can be periodic or event driven. The periodic messages carry information about the vehicle such as speed, direction and position. These information are transmitted periodically to inform surrounding vehicles and to help in detecting unusual situations [22-24]. The event driven messages are generated to inform other vehicles of an event. These messages are very important and need to be transmitted as soon as possible to prevent a life threatening situation such as a sudden car brake [25]. Convenience applications are designed to increase the comfort of the driver and the passengers. This category includes both real-time traffic information and services such as parking availability and location notification [26-30]. Finally, commercial applications [31-33] are not as important as the other two categories and they could be less welcomed in crowded traffic networks where safety and congestion of critical messages are more important. In this research, IVC, V2V, C2C and VANET are used interchangeably.

2.2 Environment and Challenges in VANET

Mobile Ad hoc Network (MANET) are networks with self-organized mobile or static nodes that follow random mobility patterns. In MANET, each node acts as a host and as a router extending the one hop coverage area of a single wireless network. Some of the examples of MANET are: Sensor Networks [34-37], Mesh Networks [38-41], and Vehicular Networks [42-44]. A VANET is a MANET with vehicles acting as the nodes. VANET is a decentralized, self-organizing network that is designed to provide communication between nearby vehicles and between vehicles and road side equipment. Nodes or vehicles move on predetermined roads, typically following a predefined mobility pattern and it is typically possible for a vehicle to get its geographic position by Global Positioning System (GPS). There are two types of communications in VANET: single hop [45, 46] and multi hop [47-49]. In single hop, a car communicates with its neighbors to advise them of an event such as braking. While in multi hop, a car communicates with other cars on the street to get information about certain services or to disseminate information. There are several factors that influence the communication in VANET, such as communication channel status (congested or not), mobility pattern and high vehicles velocity. Many challenges are facing VANETs [50-52] particularly its fast topology changes where vehicles are operating in a dynamic network and moving at fast speed, thus having very short connectivity time windows. Therefore, the communication mechanism in VANETs must be reliable.

2.3 Media Access Control (MAC)

2.3.1 MAC Layer

The Media Access Control (MAC) data communication protocol sub-layer, also known as the Medium Access Control, is part of the data link layer specified in layer 2 of the seven-layer OSI model [53]. Figure 2.1 shows a schematic of the communication between two hosts using the OSI model [54]. Each layer within an end station communicates at the same layer within another end station. Each layer has its own header containing information relevant to its role. When two hosts A and B are communicating with each other, the header in host A is passed down from the application layer to the layer below, which in turn adds its own header. The encapsulation of headers continues until they reach the physical layer. The physical layer adds the data link layer information and gets them ready to pass to host B which understands the data link information and can then strip each of the layers' headers in turn to get the data in the right location.

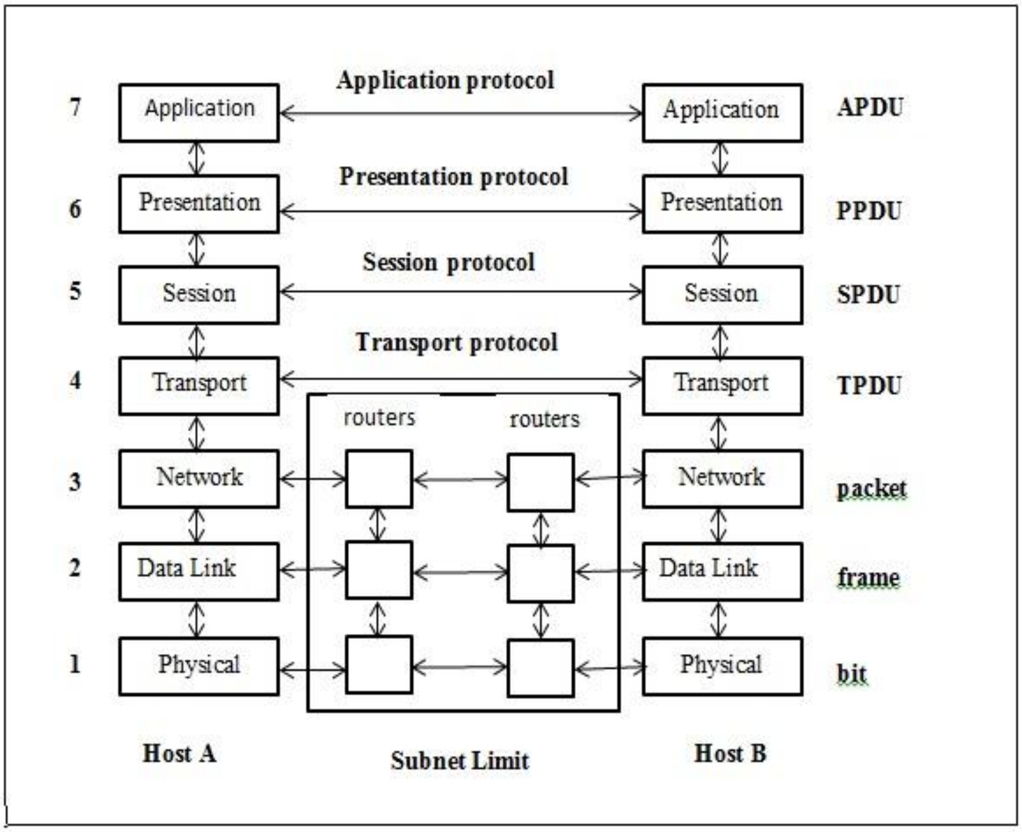


Figure 2.1: Communication between two hosts using the OSI Model [54]

MAC sub-layer acts as an interface between the Logical Link Control (LLC) sub-layer and the network's physical layer, as shown in Figure 2.2. MAC provides addressing and channel access control mechanisms that make it possible for several terminals or network

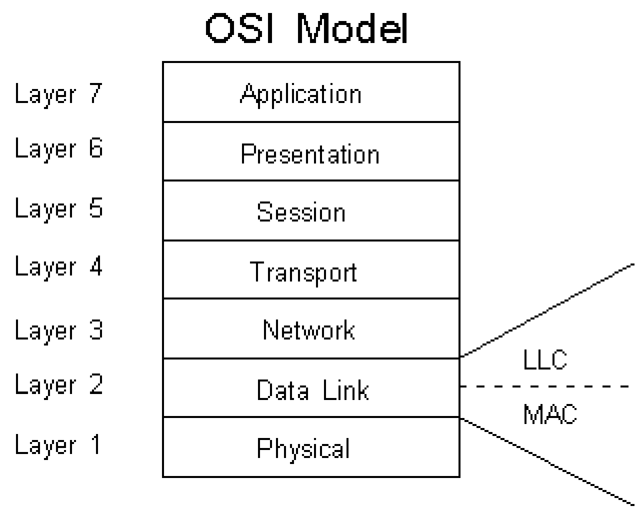


Figure 2.2: MAC sub layer in the OSI Model

nodes to communicate within a multipoint network, such as local area network (LAN) and metropolitan area network (MAN). The MAC layer emulates a full duplex logical communication channel in a multi-point network. This channel can provide unicast, multi-cast and broadcast communication services.

2.3.2 MAC Protocols

Channel access control mechanisms provided by the MAC layer are also known as multiple access protocols. These protocols make it possible for several stations connected to the same physical medium to share it. Many multiple access protocols exist for wired networks, but not all of these protocols are suitable for wireless communications. MAC protocols can be categorized into three categories based on [55]. The first category is fixed assignment protocols, examples of this category are schemes like Time Division Multiple Access (TDMA) [56-60], Code Division Multiple Access (CDMA) [61-65], and Frequency Division Multiple Access (FDMA) [66-70]. However, these protocols have problems with configuration changes because they lack flexibility in allocating resources which makes them unsuitable for rapidly changing wireless networks. The second category is the random assignment protocols which are very flexible and therefore the most commonly used in WLAN. Examples of this category are ALOHA [71-74] and Carrier Sense Multiple Access (CSMA) [75, 76]. The third category is demand assignment protocols which try to combine features of the previous two categories. Examples of this category are schemes like Token Ring, Group Allocation Multiple Access (GAMA) [77] and Packet Reservation Multiple Access (PRMA) [78]. However, more efforts are needed to implement this in a WLAN. For example, if the Token Ring is going to be implemented in a WLAN environment then all neighbors must be known first. This work focuses on random assignment protocols CSMA and ALOHA because they are the most suitable ones for wireless networks.

2.3.3 IEEE 802.11 Standard

The most common standard in Wireless Local Area Networks (WLAN) is IEEE 802.11 [79]. This wireless communication standard operates in two modes: centralized (also called infrastructure) mode and ad hoc mode.

In the infrastructure mode, wireless nodes are communicating with (and through) each other over a fixed network access points (connected to landlines) as seen in Figure 2.3. In the ad hoc mode, nodes communicate and interact directly with other nodes in their communication range without using fixed access points, where they can join or leave the network at any time, and thus the communication infrastructure is not fixed and is changing as in Figure 2.4.

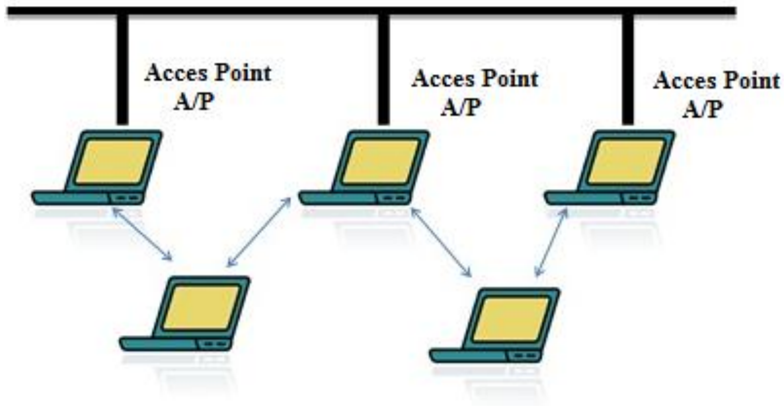


Figure 2.3: Infrastructure configuration

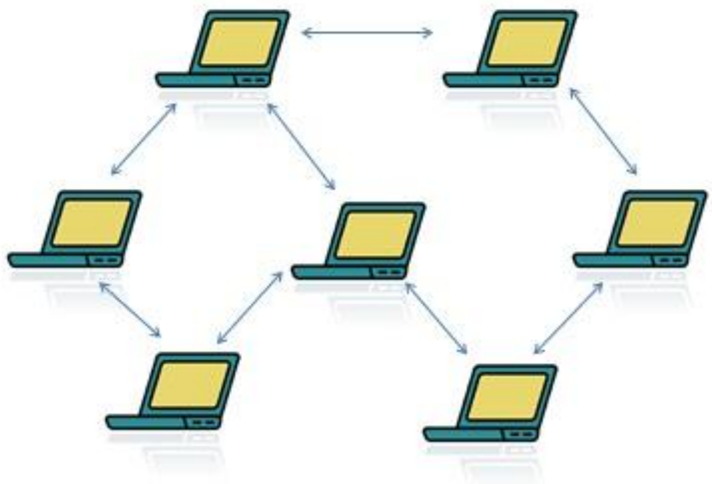


Figure 2.4: Ad-hoc configuration

IEEE 802.11 standards [79] determine the specifications for both the physical layer and the medium access control layer (MAC). There are two access mechanisms defined in the (MAC): (a) contention-based Distributed Coordination Function (DCF), and (b) polling-based Point Coordination Function (PCF).

2.3.3.1 Contention based Distributed Coordination Function (DCF)

DCF is used as the fundamental access method of the IEEE 802.11 MAC. It implements Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism and the binary slotted exponential back-off procedure to reduce packet collisions. When a station has a new packet to transmit, it checks the channel first. If the channel is sensed to be idle for duration of time called Distributed Inter Frame Space (DIFS), then the vehicle can transmit its packet. Otherwise, it backs off and keeps monitoring the channel. Once the channel measures idle for the DIFS, it starts a back-off counting process. The counter generates a random value that is chosen from a uniform distribution in the range (0, CW -1). The value of CW is doubled after each collision. If the transmission is successful, the CW value will be reset to $CW_{\min}$.

There are two techniques used for packet transmission in DCF: (a) a two-way handshaking basic access mechanism (which will be referred to as the Basic method in the rest of the dissertation) and (b) a four-way handshaking Request-To-Send/Clear-To-Send (RTS/CTS) access mechanism. In the two-way technique, after the receiver receives the transmitted data frame successfully it sends an acknowledgement (ACK) frame to the transmitter. In the RTS/CTS method, a station reserves the medium before transmission of a data frame by sending a RTS frame and receiving a CTS frame. The RTS/CTS method is designed to eliminate the interference from hidden terminals. If large packets are transmitted, then the system performance with RTS/CTS is higher than the basic method because it reduces the length of the frames involved in the contention process. However, RTS/CTS decreases efficiency because it transmits two additional frames without any payload and as the distance between transmitter and receiver increases the RTS/CTS does not work well.

2.3.3.2 Point Coordination Function (PCF)

PCF is a contention-free protocol designed for centralized networks and real time services. PCF enables stations to transmit data frames synchronously, with regular time delays between data frame transmissions which makes PCF protocol more suitable for video and control mechanisms which have higher synchronization requirements. In PCF, a point coordinator within the access point controls which stations can transmit during any given period of time. It works as follows: the point coordinator will have a list of all stations operating in PCF mode, during a time period called the contention free period (CFP) it will go through the list and poll one station at the time and grant it a permission to transmit. For example, if the point coordinator first polls station F, then during a specific period of time only station F can transmit data frames and no other station can send anything. After station F finishes its transmission, the point coordinator will then poll the next station on the list and so on. This way, each station on the list will have a chance to send its data. The IEEE 802.11 protocols make sure that the timing mechanisms used allow stations on the WLAN to alternate between the use of PCF and DCF. Therefore, the WLAN can support both synchronous and asynchronous information flow.

2.3.4 IEEE 802.11p

The IEEE 802.11p [80, 81], also called Wireless Access in Vehicular Environments (WAVE), is a multi-channel wireless standard based on the IEEE 802.11a physical standard and IEEE 802.11 MAC standard. This physical/MAC amendment of the IEEE 802.11 standard is designed for communication in VANETs, namely communications between vehicles or between vehicles and road infrastructures. Multi channels are used in WAVE, in which a control channel is used to set up transmissions and data channels are used to send data. The basic medium access mechanism used in WAVE is CSMA/CA.

Active safety applications are mostly the driving source for this amendment, where high reliability and low latency are very important. IEEE 802.11 WAVE allows high data rate up to 27 Mpbs in short distances up to 1000 meters. WAVE is part of the Dedicated Short Range Communication (DSRC) system and it operates in the licensed 5.9 GHz frequency band, with 7 channels supporting safety and non-safety applications and a 10 MHz channel bandwidth.

2.3.5 ADHOC MAC

ADHOC MAC is a MAC protocol for VANET which was conceived within the European project CarTALK2000 [82, 83]. ADHOC MAC is independent of the physical layer and it works in slotted frame structure. Because Reservation-ALOHA (R-ALOHA) [84] can coordinate the channel usage effectively in centralized networks, Reliable R-ALOHA (RR-ALOHA) protocol was proposed in [85] by extending the R-ALOHA to achieve dynamic Time Division Multiple Access (TDMA) mechanism in a distributed environment, where each vehicle selects a Basic Channel (BCH) for its own transmission. Each BCH is one time slot periodically repeated in successive frames. RR-ALOHA is considered to be the core of ADHOC MAC and, if deployed in a VANET, both the hidden and exposed terminal problems (will be discussed in the next section) are reduced and highly reliable one-hop (unicast and broadcast) and multi-hop broadcast are supported.

2.4 Hidden and Exposed Terminal Problems

A reliable communication in VANET is essential for exchanging location information. The hidden terminal and the exposed terminal problems make it difficult to provide reliable communication in wireless network because they are known to affect the throughput and fairness performance [86, 87].

2.4.1 Hidden Terminal Problem

The hidden terminal problem is a challenging problem in the decentralized and highly mobile VANET environment and it is considered the main cause of poor performance in VANET. The CSMA scheme adopted in IEEE 802.11 cannot solve this problem [88], but in a hidden terminal situation, the throughput is lower bounded to that of a simple ALOHA protocol. Many research efforts have been done to reduce the hidden terminal problem in wireless MAC protocols [89-92].

The hidden terminal problem occurs when hidden terminals, which are allowed to transmit, interfere with a receiver, causing a collision. To illustrate this problem, four wireless terminals are shown in Figure 2.5. The radio range is such that A and B are within each other's range and can potentially interfere with one another. C can also potentially interfere with both B and D, but not with A.

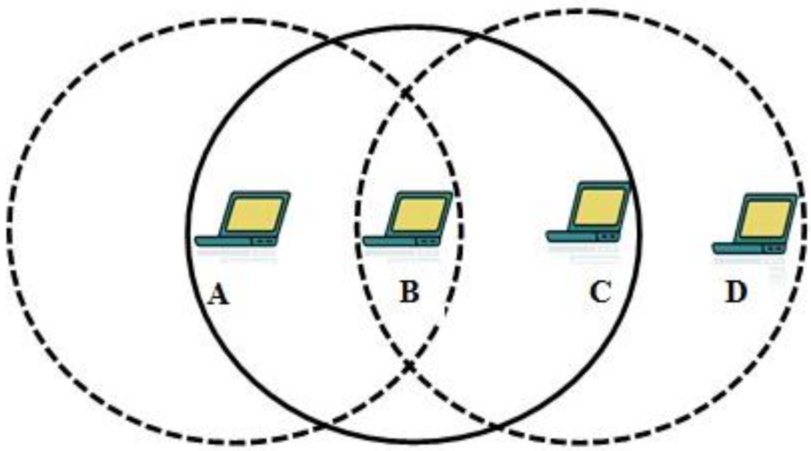


Figure 2.5: Hidden Terminal Problem

While A is transmitting to B, if C senses the medium, it will not hear A because A is out of range and thus falsely conclude that it can transmit to B. If C does start transmitting, it will interfere with the frames coming from A, causing a collision at B. The hidden terminal problem occurred when C was not able to detect a potential competitor for the medium because the competitor was too far away.

2.4.2 Exposed Terminal Problem

While there have been many research efforts done on reducing the hidden terminal problem, there have been very few research efforts addressing the exposed terminal problem. The exposed terminal problem has been discussed in great detail in [93, 94]. The exposed terminal problem occur when terminals are not allowed to transmit although they would not interfere with other terminals. To illustrate this problem, four wireless terminals are shown in Figure 2.6. The radio range is such that A and B are within each other's range and can potentially interfere with one another. C can also potentially interfere with both B and D, but not with A.

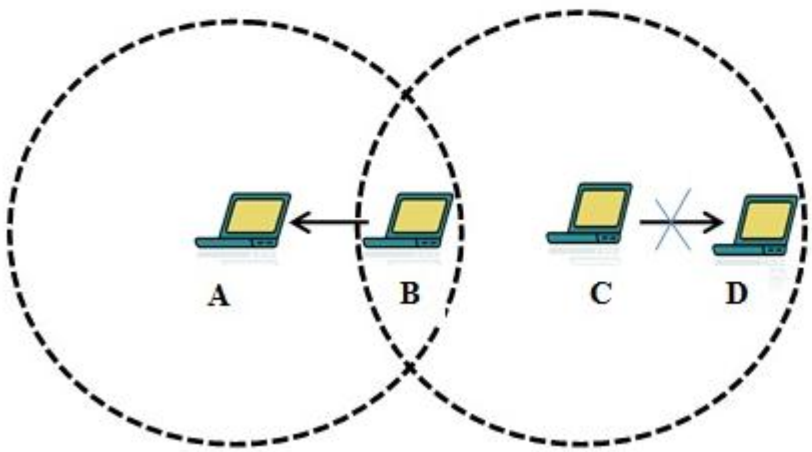


Figure 2.6: Exposed Terminal Problem

When B is transmitting to A, if C senses the medium, it will hear an ongoing transmission and falsely conclude that it may not send to D. In fact such a transmission would cause bad reception only in the zone between B and C, where neither of the intended receivers is located.

2.5 Protocols for VANET Considered in our Work

In this work, we focus on two MAC protocols, CSMA and ALOHA. They are the most commonly used and considered by many to be the best candidate for VANETs.

2.5.1 CSMA

CSMA is a contention based protocol and its performance has been studied both analytically and by simulation in many papers such as [75, 76, 95-97]. CSMA ensures that before any station attempts to transmit, it first senses the medium and defers to any ongoing transmission. If the sensed energy in the medium is above a specific threshold, it usually means that another station is transmitting. There are two extensions to CSMA, CSMA with Collision Detection (CSMA/CD) and CSMA with Collision Avoidance (CSMA/CA). In the former, a transmission is stopped once the sender detects a collision to reduce the overhead of a collision. In the CSMA/CA, the main goal is to avoid collisions, which is achieved by making the sender wait for an inter frame spacing (IFS) time before contending for the channel after the channel becomes idle. This works as follows: when a station wants to transmit a frame, it first senses the medium and then waits for a certain amount of time, depending on the CSMA mechanism used.

In p-persistent CSMA mechanism, the sender sends a packet with probability p as soon as the carrier is idle. In a non-persistent CSMA mechanism, if the sender senses the channel and senses that it is busy, the sender waits for a random amount of time and then tries to transmit again instead of continuously monitoring the channel. The collision avoidance aspect of the protocol also can be achieved by RTS/CTS exchanges where the sender and the receiver exchange packets before they start the actual transmission to ensure the transmission is successful.

2.5.2 ALOHA

ALOHA is a simple packet acknowledgment scheme (named so because of its creation at the University of Hawaii). In this protocol, the terminal sends data whenever it has data to send and the base station will then respond with an acknowledgment of some kind. Although the algorithm is simple, it is revolutionary by opening up the possibilities of multiple terminals sharing a single channel. The throughput however drops drastically as the number of terminals increases.

To resolve the throughput problem, the channel is divided into slots, each one packet long, by some coordinating signal, usually from a base station. The new protocol, called slotted ALOHA or S-ALOHA, allows collision to occur only directly, meaning there is no longer the possibility of the end of one packet interfering with the beginning of another packet. This allows slightly more traffic but still lacks the desired performance. Reservation is then added to ALOHA (R-ALOHA) making the throughput for multi-packet messages comparatively high. With reservation, a terminal may reserve a slot after one successful packet transmission. In a multi-packet system, this guarantees throughput for a terminal after the first successful packet, assuming there is no hidden terminal. Analytical studies and simulations of R-ALOHA can be found in [98-100]. However, one problem that is not considered is the lack of priority in the evolved ALOHA schemes.

CHAPTER

3. NEW BACK-OFF SCHEME FOR CSMA/CA

3.1 Introduction

Distributed Coordination Function (DCF) is the basis of the IEEE 802.11 WLAN MAC protocol, which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and binary slotted exponential back-off scheme to reduce packet collision. DCF implementation specified by the IEEE 802.11 standard resets the contention window (CW) to the minimum value upon completing a successful transmission. Although the new CW is minimal, the congestion level goes gradually to minimum, causing the node to probably waste time and channel bandwidth going through several collisions and retransmissions before reaching a CW value that corresponds to the congestion level.

In this chapter, we provide a new analytical model that modifies the implementation to reduce the window to half its size after a successful transmission. Both analytical and simulation analysis are used in our model to investigate the IEEE 802.11 DCF throughput in a non-ideal channel with channel induced errors and capture effects under saturated traffic conditions.

3.2 Markov Model

Our model provides a new analytical model for evaluating the saturation throughput under the following assumptions:

1. Non ideal channel conditions (capture effects and channel induced errors).
2. Fixed number of contending stations.
3. Probability of collision, P_{col}, is constant and independent of the number of collisions already suffered.

In our analysis, we first determined the transmission probability τ of each station in a randomly chosen time slot by studying the behavior of a single station with a Markov model. Then, by studying the events in a generic time slot, we expressed the throughput as a function of τ.

3.3 Packet Transmission Probability

Let n be the number of contending stations where each station operates under the saturation condition (i.e., there is always a packet available for transmission). The *Contention Window* is represented by the value w which depends on the number of failed transmissions for the packet. At each packet transmission, the back-off time is uniformly chosen in the range $(0,...,w-1)$. The back-off time counter of a window size for a given station at slot time t is represented by the stochastic process $b(t)$. The back-off stage is in the range of $(0,...,m)$ and it is represented by the stochastic process $s(t)$, where m is the maximum back-off stage.

In the first transmission attempt, w is set to the minimum contention window value $W = CW_{min}$. This value is doubled after each unsuccessful transmission up to a maximum value of $CW_{\max} = 2^m W$. At any back-off stage i, the contention window is represented by $W_i = 2^i W$, where $i \in (0, m)$. After a successful transmission, the contention window will be reduced to half its size.

In a non-ideal channel, collisions on the transmitted packets can occur with probability (P_{col}) and transmission errors due to the channel can occur with probability (P_e). When either of these two happens the transmission is considered unsuccessful. The probability of failed transmission (p) can be therefore expressed as:

$$p = P_{col} + P_e - P_{col}.P_e \quad (3.1)$$

The discrete-time Markov chain was used to model the bi-dimensional process $\{s(t), b(t)\}$ as shown in Figure 3.1

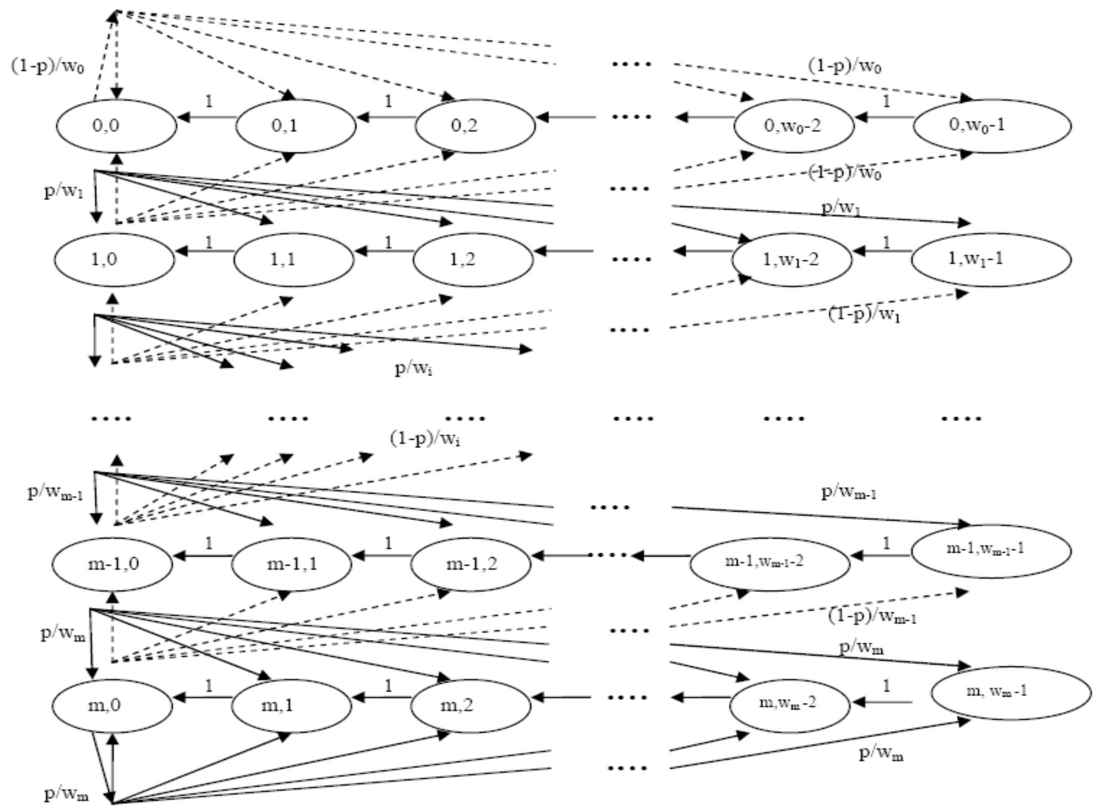


Figure 3.1: Schematic of the Markov chain model of our new back-off window model.

In this Markov chain, the only non-null one-step transition probabilities are:

$$
\left.
\begin{array}{lll}
P\{i,k \mid i,k+1\} = 1, & k \in (0, W_i - 2) & i \in (0, m) \\
P\{0,k \mid 0,0\} = (1-p)/W_0, & k \in (0, W_0 - 1) & i = 0 \\
P\{i-1,k \mid i,0\} = (1-p)/W_{i-1} & k \in (0, W_{i-1} - 1) & i \in (1, m) \\
P\{i,k \mid i-1,0\} = p/W_i & k \in (0, W_i - 1) & i \in (1, m) \\
P\{m,k \mid m,0\} = p/W_m & k \in (0, W_m - 1) & i = m
\end{array}
\right\} \quad (3.2)
$$

The first equation given in (3.2) accounts for the decrements of the back-off timer at the beginning of each time slot. The second equation in (3.2) indicates that, at stage 0, if the transmission is successful then the back-off timer of the new packet starts from back-off stage 0. The third equation in (3.2) accounts for starting the back-off timer of the new packet from back-off stage $i-1$ after a successful transmission. The fourth equation in (3.2) indicates that every unsuccessful transmission increases the back-off stage from $i-1$ to stage i. In the fifth equation in (3.2), the back-off stage is not increased in subsequent packet transmissions once it reaches the value m.

Let $b_{i,k}$ be the stationary distribution of the Markov chain. From the Markov chain model shown in Figure 3.1, we obtain a closed-form solution for the chain.

$$b_{i,0} = p \cdot b_{i-1,0} + (1-p) \cdot b_{i+1,0} \qquad 0 < i < m \tag{3.3}$$

$$b_{m,0} = p \cdot b_{m-1,0} + p \cdot b_{m,0} \qquad i = m \tag{3.4}$$

By simplification of equations (3.3) and (3.4), we obtain the following:

$$b_{i,0} = \left(\frac{p}{1-p}\right)^{i} \cdot b_{0,0} \qquad 0 \le i \le m \tag{3.5}$$

Because of the chain regularities, for each $k \in (1, W_i - 1)$, the stochastic states $b_{i,k}$ can be represented as follows:

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p)b_{0,0} + (1-p)b_{1,0} & i = 0 \\ p.b_{i-1,0} + (1-p)b_{i+1,0} & 0 < i < m \\ p.(b_{m-1,0} + b_{m,0}) & i = m \end{cases} \tag{3.6}$$

According to equations (3.5) and (3.6), all the values of $b_{i,k}$ are dependent on $b_{0,0}$. Therefore, equation (3.6) can be written as:

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \qquad 0 \le i \le m \quad k \in (0, W_i - 1) \tag{3.7}$$

The value of $b_{0,0}$ can be determined by using the normalization condition for stationary distribution:

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2}$$

$$= \frac{b_{0,0}}{2} \left[\frac{(1-2p)[W(1-p)^{m+1} - W(2p)^{m+1}]}{(1-3p)(1-2p)(1-p)^m} + \frac{(1-3p)[(1-p)^{m+1} - p^{m+1}]}{(1-3p)(1-2p)(1-p)^m} \right] \tag{3.8}$$

From the simplification of equation (3.8), we get:

$$b_{0,0} = \frac{2(1-3p)(1-2p)(1-p)^m}{(1-2p)[W(1-p)^{m+1} - W(2p)^{m+1}] + (1-3p)[(1-p)^{m+1} - p^{m+1}](1-3p)(1-2p)(1-p)^m} \tag{3.9}$$

Recall that the probability that a station transmits in a randomly chosen time slot is τ. Using equations (3.5) and (3.9), the value of τ can be expressed as:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{(1-p)^{m+1} - p^{m+1}}{(1-p)^{m}(1-2p)} \cdot b_{0,0}$$

$$= \frac{2(1-3p)((1-p)^{m+1} - p)}{(1-2p)[W(1-p)^{m+1} - W(2p)^{m+1}] + (1-3p)[(1-p)^{m+1} - p^{m+1}]} \quad (3.10)$$

At $m = 0$, the exponential back-off is not considered and the probability of τ will be independent of p. Therefore, equation (3.10) becomes:

$$\tau = \frac{2}{W+1} \quad (3.11)$$

At steady state, each station transmits a packet with probability τ. The collision probability, P_{col}, of a packet being transmitted is the probability that at least one of the $n-1$ remaining stations transmits. Thus,

$$P_{col} = 1-(1-\tau)^{n-1} - P_{cap} \quad (3.12)$$

where P_{cap} is the probability of capture and the mathematical formula for it as presented in [101] is given by

$$P_{cap} = \sum_{i=1}^{n-1} \binom{n}{i+1} \tau^{i+1}(1-\tau)^{n-i-1} P_{cp}(\gamma > z_0 g(S_f) \mid i) \quad (3.13)$$

$$P_{cp}(\gamma > z_0 g(S_f) \mid i) = \frac{1}{[1+z_0 g(S_f)]^{i}} \quad (3.14)$$

where γ is the power ratio of the useful signal and the sum of the powers of the i interfering channel contenders simultaneously transmitting i frames, $g(S_f)$ is the inverse of the processing gain, and z_0 is the capture ratio.

3.4 Throughput

The normalized system throughput S is defined as the fraction of time of using the channel to transmit successfully the payload bits. The following formula is used to calculate the system throughput in an ideal channel [102]:

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s)T_c} \tag{3.15}$$

For our model, we assume non ideal channel conditions where both channel induced errors and capture effects are considered. The following expression can be used to calculate the throughput:

$$S = \frac{P_s P_{tr}(1-P_e)E[P]}{(1-P_{tr})\sigma + P_{tr} P_s (1-P_e) T_s + P_{tr}(1-P_s)T_c + P_{tr} P_s P_e T_e} \tag{3.16}$$

where

$$P_{tr} = 1-(1-\tau)^n \tag{3.17}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1} + P_{cap}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1} + P_{cap}}{1-(1-\tau)^n} \tag{3.18}$$

P_{tr} is the probability that there is at least one transmission in the considered time slot. P_s is the probability of successful transmission occurring on the channel. P_e is the probability of channel induced errors. T_s is the average time in which the channel is sensed busy because of a successful transmission. T_c is the average time the channel is sensed busy by each station during a collision. T_e is the average time the channel is sensed busy by each station from a frame suffering transmission errors. σ is the duration of an empty time slot, and $E[P]$ is the average packet payload size.

Equation (3.16) can be used to calculate the throughput for both Basic and RTS/CTS methods, but first we have to specify T_s and T_c that correspond to the mechanism used. T_s and T_c values for the Basic and RTS/CTS mechanisms can be calculated using expressions in [102].

3.5 Analysis and Results

For our simulations and theoretical analysis we used the network parameters listed in Table 3.1. Figures 3.2 - 3.7 show our analytical results and Figures 3.8 and 3.9 show the simulation results. Figure 3.2 shows the saturation throughput for our model under ideal channel conditions (no channel induced errors or capture effects) and compare it to the previous Bianchi's model [102]. Note that the throughput of the new model is much higher than Bianchi's for the basic access method.

TABLE 3.1: CSMA/CA System parameters

Packet Payload	8184 bits
PHY header	128 bits
MAC header	272 bits
SIFS	28 μs
DIFS	128 μs
ACK	112 bits + PHY header
CTS	112 bits + PHY header
RTS	160 bits + PHY header
$CW_{\min}$	31
Slot time (σ)	50 μs
Propagation delay (δ)	1 μs

For example, using 50 stations, the new model has a throughput of nearly 0.78 while Bianchi's is about 0.55. When using RTS/CTS method, the new model showed a little throughput improvement. This is expected, because the collision time is already reduced to a small value by RTS/CTS. Figure 3.3 shows that the ratio of throughput increases steadily with the number of stations up to nearly 40% at 50 stations for basic access, while it is within 2% for RTS/CTS access.

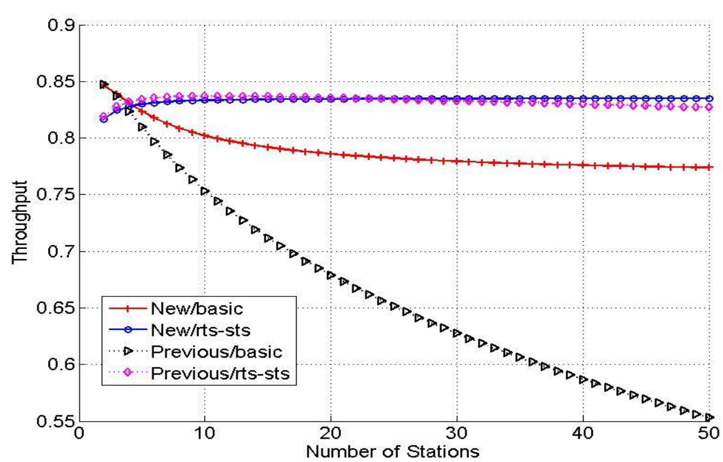


Figure 3.2: Saturation throughput for new model and the previous (Bianchi's) model for both Basic and RTS/CTS access mechanisms in ideal channel.

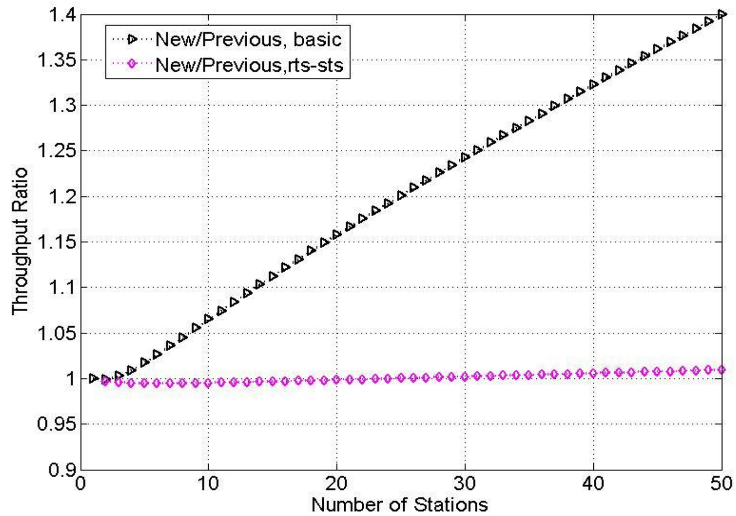


Figure 3.3: Ratio of throughput for the new and previous (Bianchi's) model as a function of the number of stations for Basic and RTS/CTS access mechanisms.

Figures 3.4 and 3.5 compare the throughput of our model under non-ideal channel conditions (with channel errors and capture effects) to the throughput of Bianchi's model (under ideal channel) for both the Basic and RTS/CTS methods. The results show that, for the Basic method, even under non-ideal channel condition our model performs better as the number of stations increase. For example, it is 7% better than Bianchi's when the number of stations is 10 but the performance is 18% better when the number of stations is 50. But when RTS/CTS is used, our model performs 21% less than Bianchi's. These results indicate that under non-ideal channel conditions our model is best used when the Basic access mechanism is used.

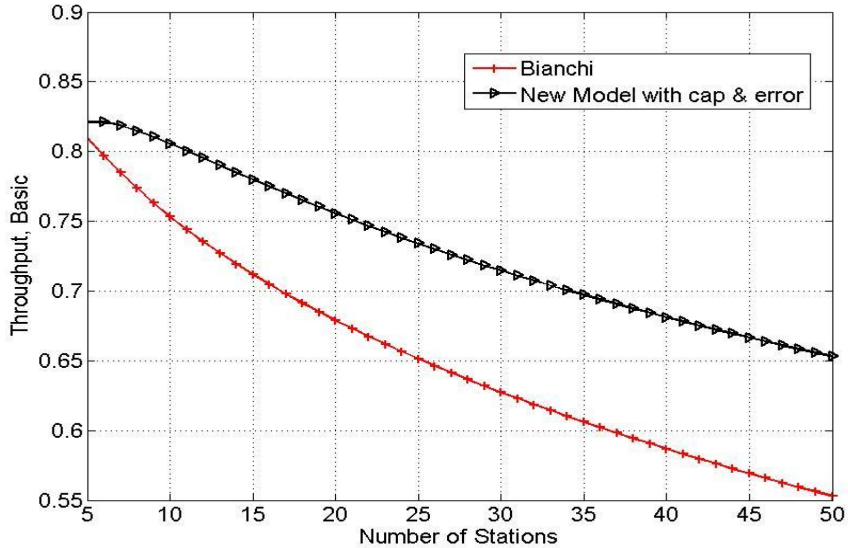


Figure 3.4: Saturation throughput of the new model under non ideal channel conditions compared to Bianchi's model under ideal channel conditions for the Basic access mechanism.

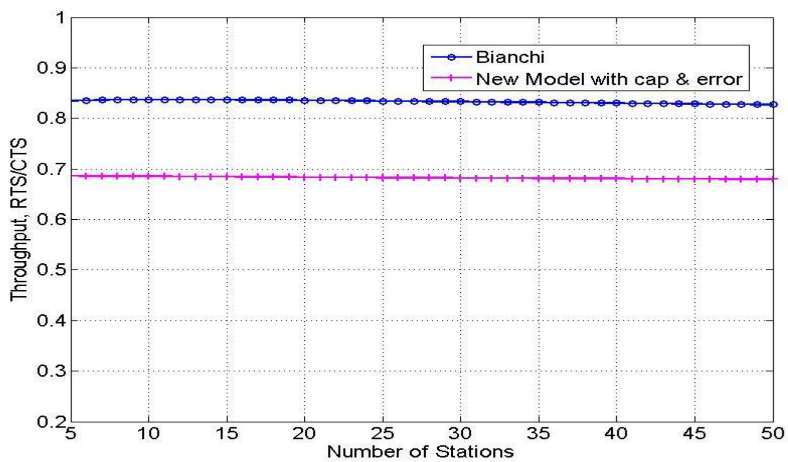


Figure 3.5: Saturation throughput of the new model under non ideal channel conditions compared to Bianchi's model under ideal channel conditions for the RTS/CTS access mechanism.

Figures 3.6 and 3.7 show that, when the Basic method is used, the throughput of our model under ideal channel conditions and non-ideal channel conditions is almost the same for low number of stations up to 10 stations. However, after that the throughput of non-ideal channel starts decreasing as the number of stations increases until it reaches

18% lower than an ideal channel for 50 stations. The throughput for RTS/CTS under non-ideal channel is always less than the throughput under ideal channel by about 21%.

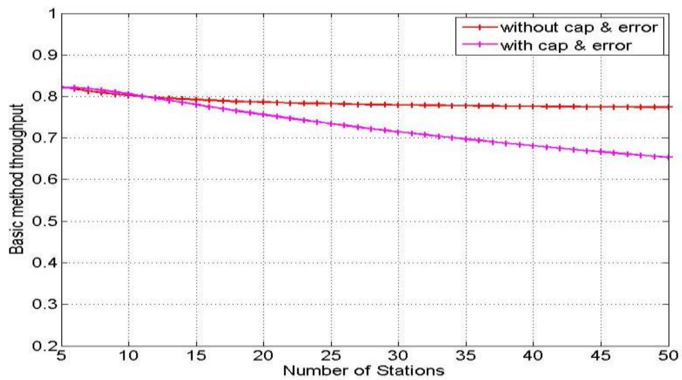


Figure 3.6: Throughput of new model is higher in ideal channel (without capture and channel errors) than in non-ideal channel (with capture and channel errors) for the Basic access mechanism.

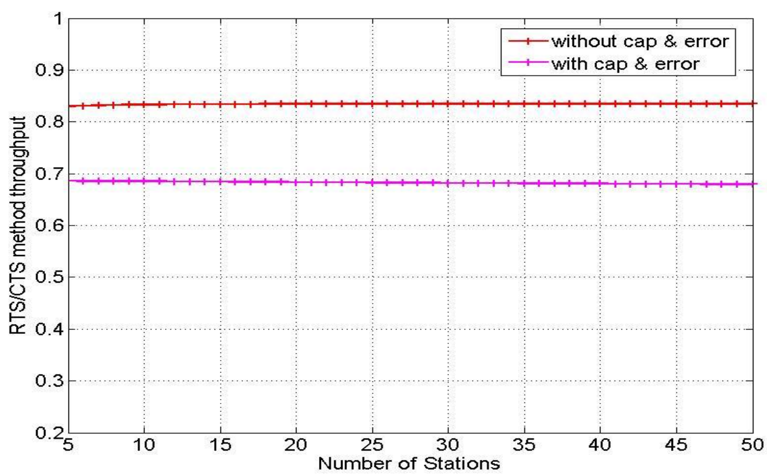


Figure 3.7: Throughput of new model is higher in ideal channel (without capture and channel errors) than in non-ideal channel (with capture and channel errors) for RTS/CTS access mechanism.

To validate our new Markov model, Monte Carlo simulation was used under ideal channel conditions. The simulation as shown in Figures 3.8 and 3.9 agrees with the analysis, particularly when the number of stations is large. The simulation agrees with the new model within 1% and 4.7% when the RTS/CTS and the Basic methods are used, respectively.

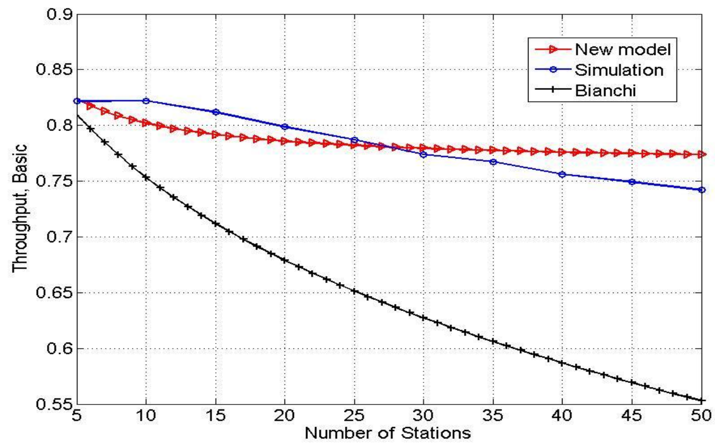


Figure 3.8 Analysis versus simulations for the Basic access mechanism.

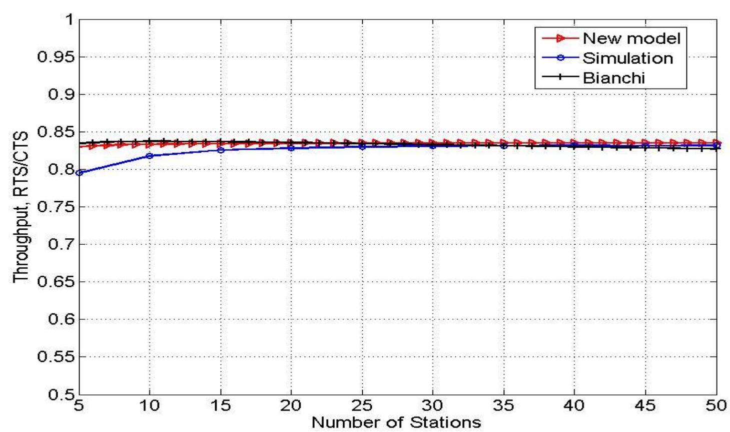


Figure 3.9: Analysis versus simulations for the RTS/CTS access mechanism.

3.6 Summary

In this chapter, an analytical model of the IEEE 802.11 MAC based on a two dimensional discrete time Markov chain is introduced. The Bianchi's model was modified by halving the contention window after every successful transmission. For the

Basic method, the analytical model results show that the throughput was improved under both ideal channel conditions and non-ideal channel conditions (with capture effect, channel-induced errors). In comparison with the standard implementation, the throughput has improved by 40% under ideal channel conditions and up to 10 % in non-ideal channel conditions for the Basic access method. The Markov model was validated by Monte Carlo simulations under ideal channel conditions. The new model is best used when the basic access mechanism is implemented under non-ideal channel conditions with a large number of contending stations.

CHAPTER

4. PRIORITY R-ALOHA (PR-ALOHA)

4.1 Introduction

This chapter introduces a new ALOHA based protocol called Priority R-ALOHA (PR-ALOHA) with a two-level priority scheme that includes high and low priority. An inter-vehicle communication simulation is performed to test the new protocol and evaluate its performance, including both throughput and delay for each priority level. Furthermore, communication errors and capture effects are considered in our simulation.

4.2 R-ALOHA

The R-ALOHA protocol has been discussed in several papers [98-100, 103, 104]. The standard R-ALOHA algorithm divides a single channel into regular time slots called frames. A frame repeats periodically depending on the specified length. The frame is further subdivided into slots as shown in Figure 4.1

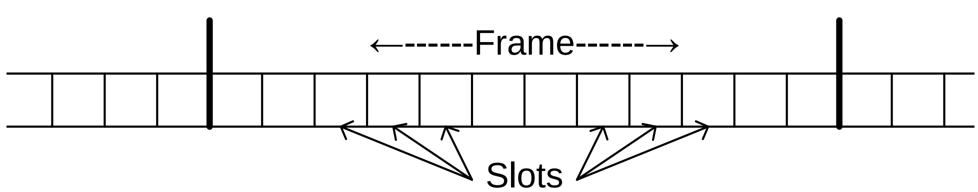


Figure 4.1: Frame architecture of R-ALOHA

In R-ALOHA, if the terminal has a message to transmit it attempts to reserve a slot. A slot is successfully reserved if the terminal uses it to successfully transmit its first packet. If the slot is successfully reserved, the terminal will transmit during that slot on every consecutive frame until the message is completely transmitted successfully or a transmission error occurs. There are two possible signaling architectures: slot-by-slot or frame-by-frame. The slot-by-slot signaling allows a packet to contend for a new slot based on a given permission probability in every slot where terminals in the network are notified of the current reservation status at the beginning of every slot. The frame-by-frame signaling allows all packets to contend once per frame. This is realized by certain frame-by-frame control signaling strategies like setting additional slot in each frame or arranging an exclusive signaling channel in the system [105]. This study uses frame–by-frame signaling where every terminal in the network will be notified of the current reservation status at the beginning of each frame. Each terminal that has a message but has not yet reserved a slot will randomly select an unreserved slot and attempt to reserve it. If there is a packet conflict or a transmission error, the packet must be retransmitted in the next frame. The application considered here is a mobile broadcast environment with no base station.

4.3 Capture Effects and Transmission Error

4.3.1 Capture Effects

If more than one packet competes simultaneously for the same slot, a collision will occur. As a result, the packets are destroyed and both terminals lose their chances of reserving the slot. However, with capture effects [106], the slot is captured (reserved) by one of the terminals. We use the same method as in [107] to calculate the probability of capture.

The probability q_n that one out of n users captures the receiver is given by the following:

$$q_n = nq(n \mid z) \tag{4.1}$$

where z is the capture ratio and $q(n \mid z)$ is the capture probability for n colliding packets which is given by the following equation [107]:

$$\begin{aligned}
q(n \mid z) &= \frac{2}{\sqrt{\pi}} \int_0^1 \int_{-\infty}^{\infty} r_1 \exp(-x_1^2) \\
&\cdot \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} f(x_1, y_1) \exp(-y_1^2) dy_1 \right] dx_1 dr_1 \\
&\cdot \frac{2}{\sqrt{\pi}} \int_0^1 \int_{-\infty}^{\infty} r_2 \exp(-x_2^2) \\
&\cdot \left[\frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} f(x_2, y_2) \exp(-y_2^2) dy_2 \right]^{(n-1)} dx_2 dr_2
\end{aligned} \tag{4.2}$$

where

$$f(x_1, y_1) \equiv \left[\sqrt{z} \cdot r_1^2 \cdot \exp\left\{ \frac{\sqrt{2}}{2} \sigma_s \left(y_1 - x_1 \right) \right\} \right] \cdot \arctan \left[\frac{1}{z r_1^4} \exp\left\{ \frac{\sqrt{2}}{2} \sigma_s \left(x_1 - y_1 \right) \right\} \right]$$

$$f(x_2, y_1) \equiv \left[\sqrt{z} \cdot r_2^2 \cdot \exp\left\{ \frac{\sqrt{2}}{2} \sigma_s \left(y_2 - x_2 \right) \right\} \right] \cdot \arctan \left[\frac{1}{z r_2^4} \exp\left\{ \frac{\sqrt{2}}{2} \sigma_s \left(x_2 - y_2 \right) \right\} \right]$$

(4.3)

and where σ_s is the logarithmic standard deviation of the lognormal distribution of the received power due to the effects of multipath fading and shadowing.

4.3.2 Transmission Error

In a wireless channel, transmission errors occur due to multipath and mobility. If each packet holds L bits, then the packet transmission error, P_e, happens if $\varepsilon + 1$ error bits have been received. When this occurs, the slot will be released and it will be available for contending terminals to try to reserve it again. The packet transmission error probability can be calculated by [108]:

$$P_e = \sum_{i=\varepsilon+1}^{L} \binom{L}{i} P_b^i (1 - P_b)^{L-i} \tag{4.4}$$

4.4 Priority R-ALOHA (PR-ALOHA)

The new extension to the reservation scheme is a two level priority access. First a pre-specified number of slots are randomly chosen as high priority slots. These slots are reserved exclusively for high priority traffic. When a normal priority message appears it may contend for any empty slot except the ones reserved for high priority traffic. When a high priority message is generated, it may contend for any empty slot, including those slots not reserved for high priority, as shown in Figure 4.2. This effectively increases the number of slots that a high priority packet may compete for and thus decreases the delay.

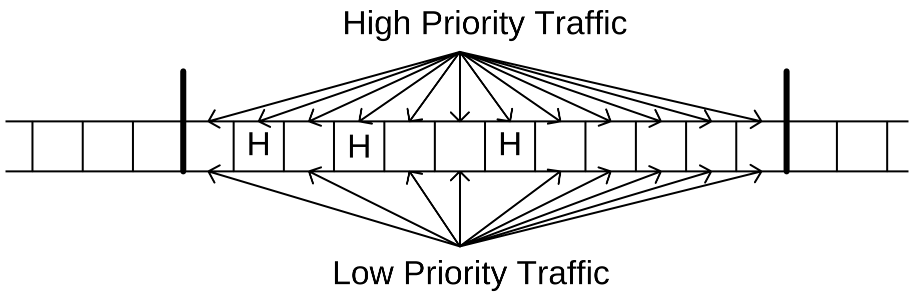


Figure 4.2: Frame architecture of PR-ALOHA

4.5 Modeling Issues and Performance Analysis

A terminal is a message generating entity. The simulation of the protocol is performed from the perspective of one such terminal. The computer simulation assumes a fixed frame size of 16 slots. The terminals produce messages according to the following scheme. At the beginning of each frame, all terminals that do not have a message are given the opportunity to produce one. 50% of these empty terminals produce a message at the beginning of each frame. Each message consists of 4 packets. When a terminal has successfully transmitted 4 consecutive packets, the message is considered sent and the terminal is considered empty again. For traffic priority simulations, a certain percentage of the generated traffic is assumed to be high priority while the rest of the traffic is assumed to be low priority. In our simulation, the capture effect is considered and the transmission error is calculated using equation 4.2. The system parameters used in the simulation are listed in Table 4.1. If a terminal experiences a transmission error then it loses its slot reservation and must compete again for an available slot and attempt to retransmit its message again. The simulation is performed with and without the priority scheme and the results are compared.

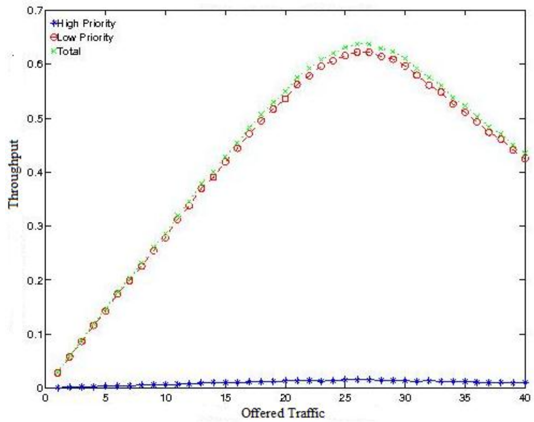
TABLE 4.1: PR-ALOHA System parameters

Packet size	1024 bits
Bit error rate	0.001
Bit error threshold	3
Packets/Message	4
Number of frames in trial	100000 frame
Capture effect- σ	6
Capture effect- α	3
Slots/frame	16

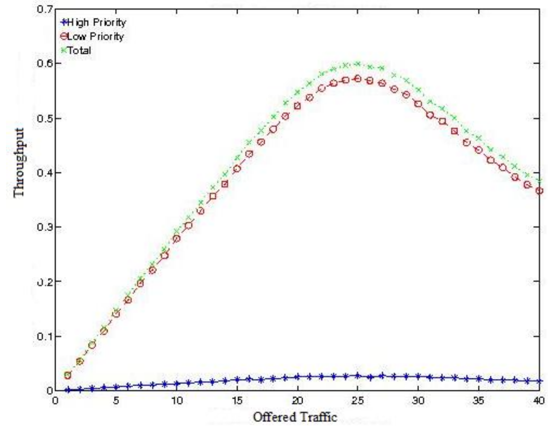
4.6 Numerical Results and Discussions

The results of the simulation show a tradeoff between the throughput and the high priority delay. Figure 4.3 shows throughput versus the number of offered traffic. As the number of slots reserved for high priority traffic increases from 1 to 8 slots, the throughput for low priority traffic (colored red) decreases, the throughput for high priority traffic (colored blue) increases and the total throughput (colored green) decreases as shown in sub-figures a to h.

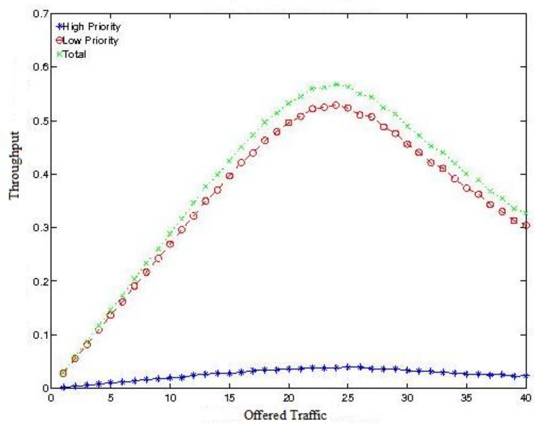
a (1 high priority slots)



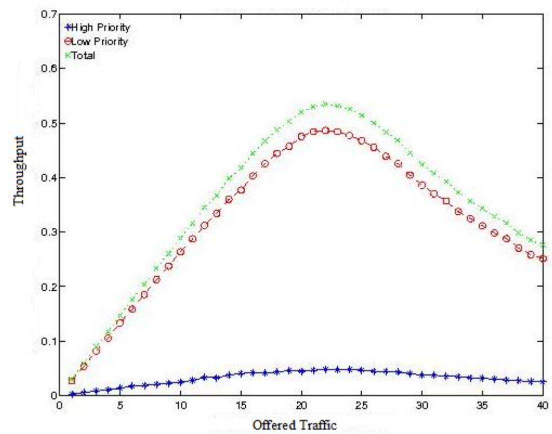
b (2 high priority slots)



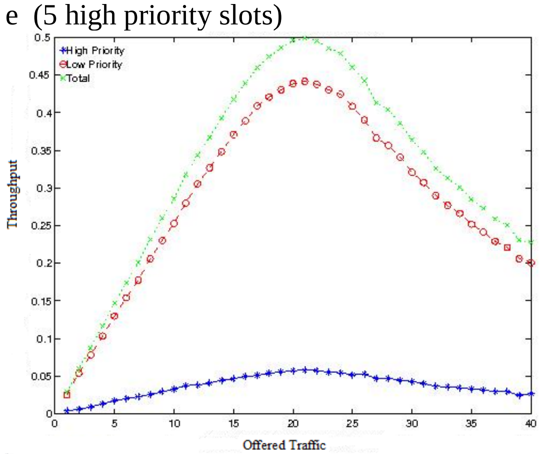
c (3 high priority slots)



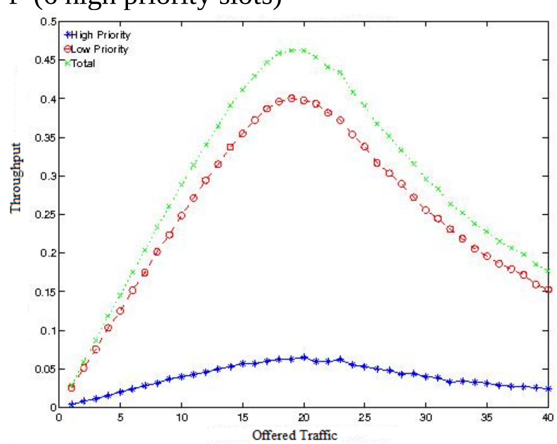
d (4 high priority slots)



e (5 high priority slots)



f (6 high priority slots)



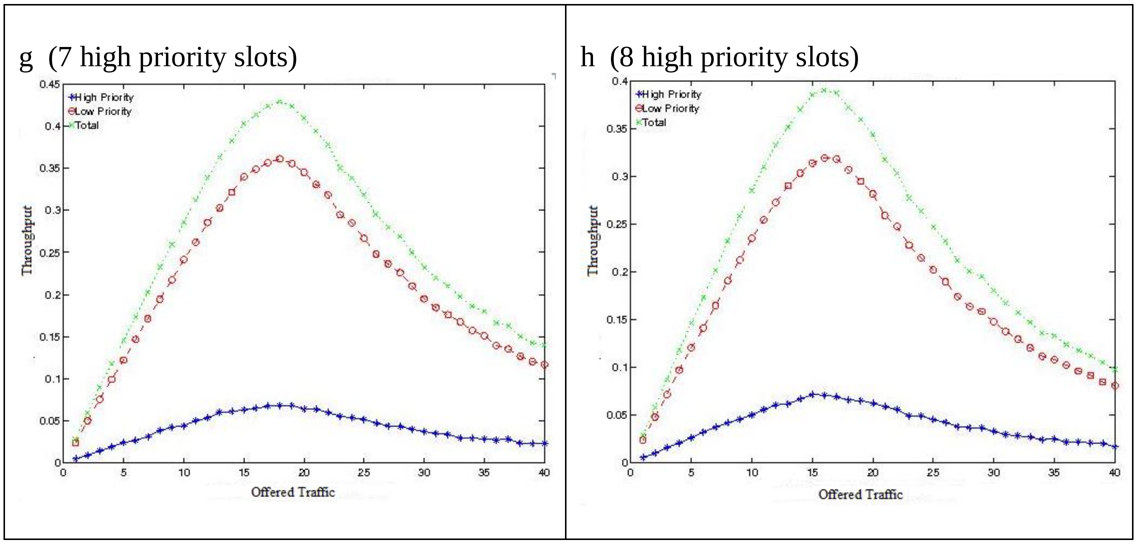
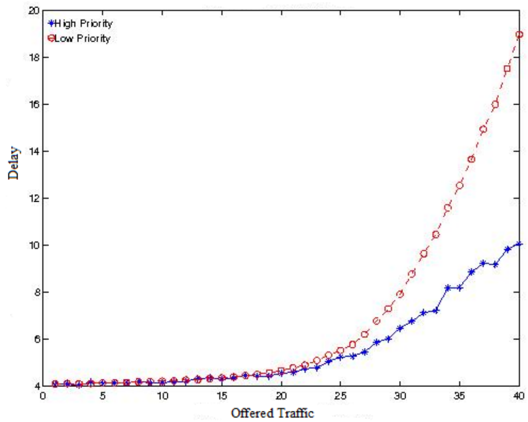


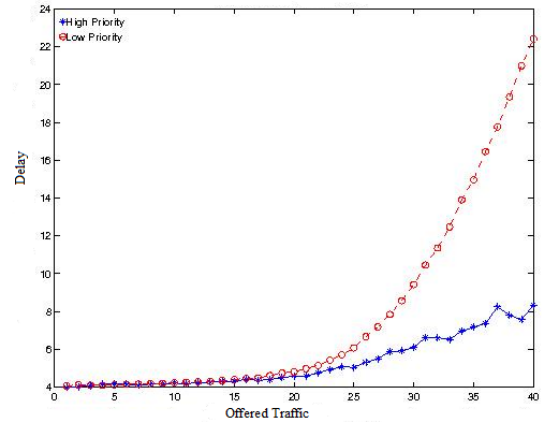
Figure 4.3: Throughput vs. Offered traffic for different number of high priority slots (1 to 8).

Figure 4.4 shows the delay (as measured by the number of frames required to transfer a message) as a function of the number of offered traffic. As the number of slots reserved for high priority traffic increases from 1 to 8 slots the delay of high priority decreases and the delay of low priority increases.

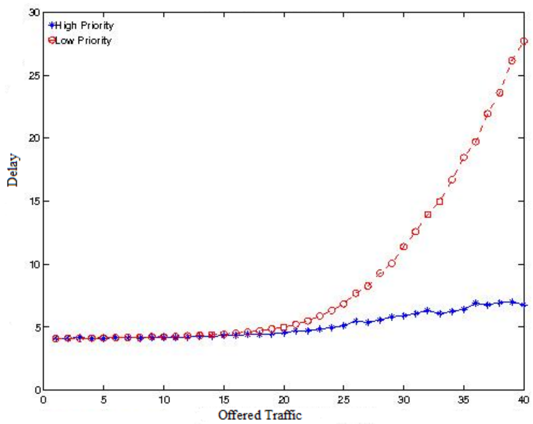
a (1 high priority slots)



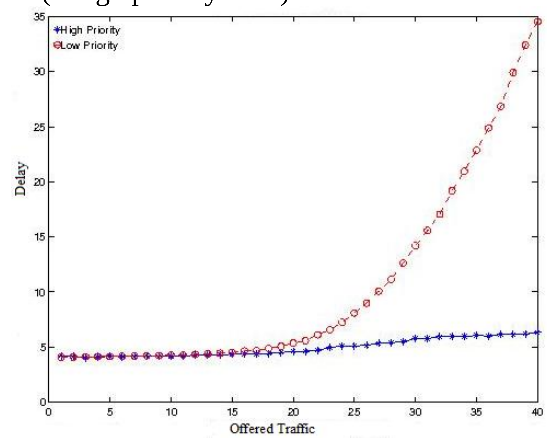
b (2 high priority slots)



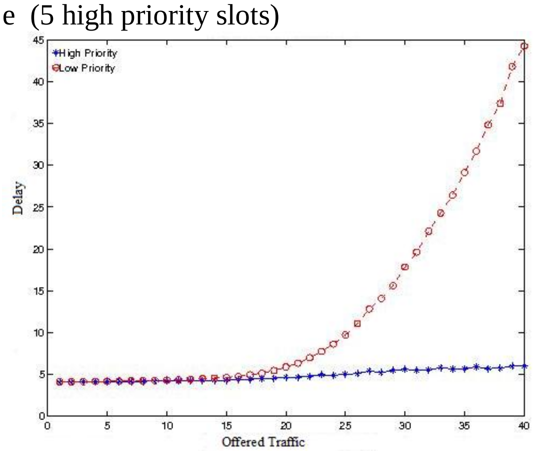
c (3 high priority slots)



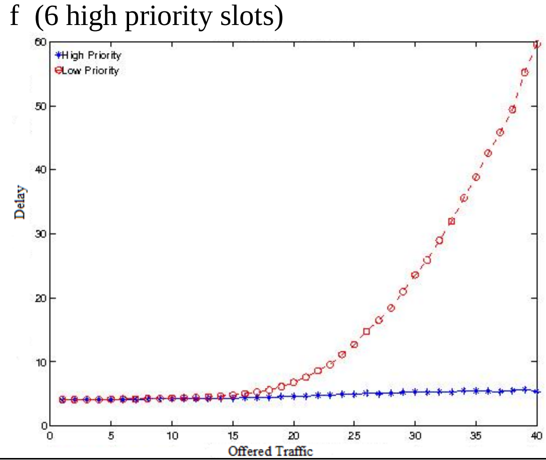
d (4 high priority slots)



e (5 high priority slots)



f (6 high priority slots)



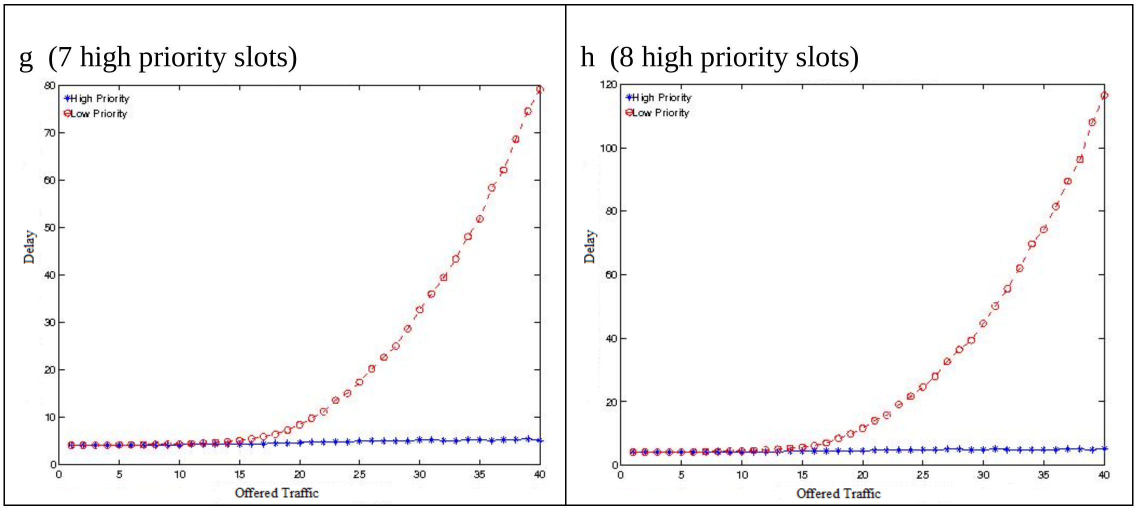


Figure 4.4: Delay vs. offered traffic for different number of high priority slots (1 to 8).

Figure 4.5 shows a comparison of the delay of high and low priority traffic with and without priority slots. With priority slots, the delay of high priority traffic is 7 frames and that of low priority is 13 frames for 40 terminals. Without priority, the delay for high and low priority traffic is the same (10 frames) for 40 terminals. Figure 6 shows that the total achieved throughput with priority (high and low) slots is 3% less than that without priority slots. The reduction of throughput is due to unused slots (by the low priority traffic) marked for high priority. An optimal algorithm maybe used to minimize the effect by allocating high priority slots in proportion to the high priority traffic being generated.

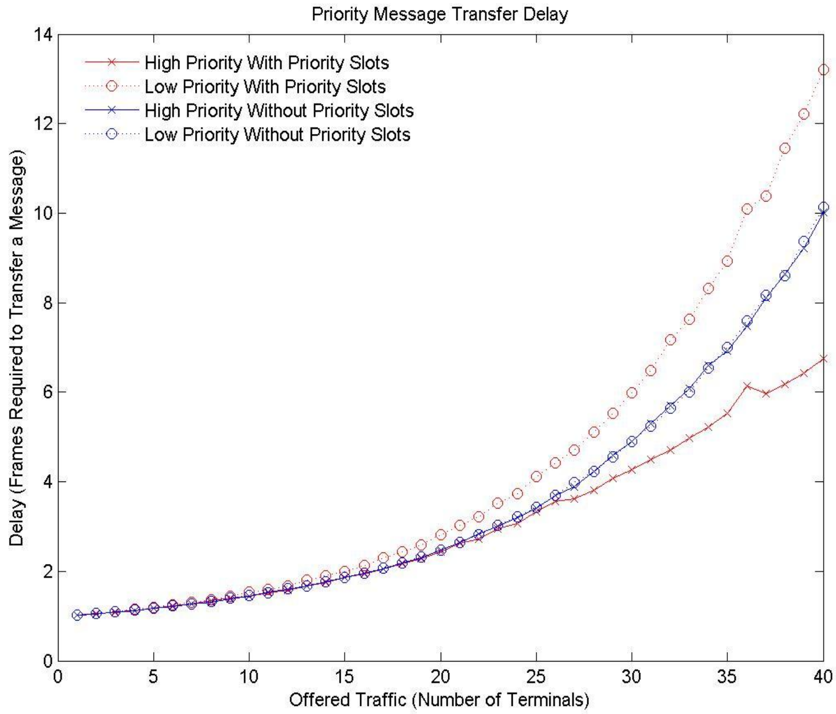


Figure 4.5: Delay with and without priority slots.

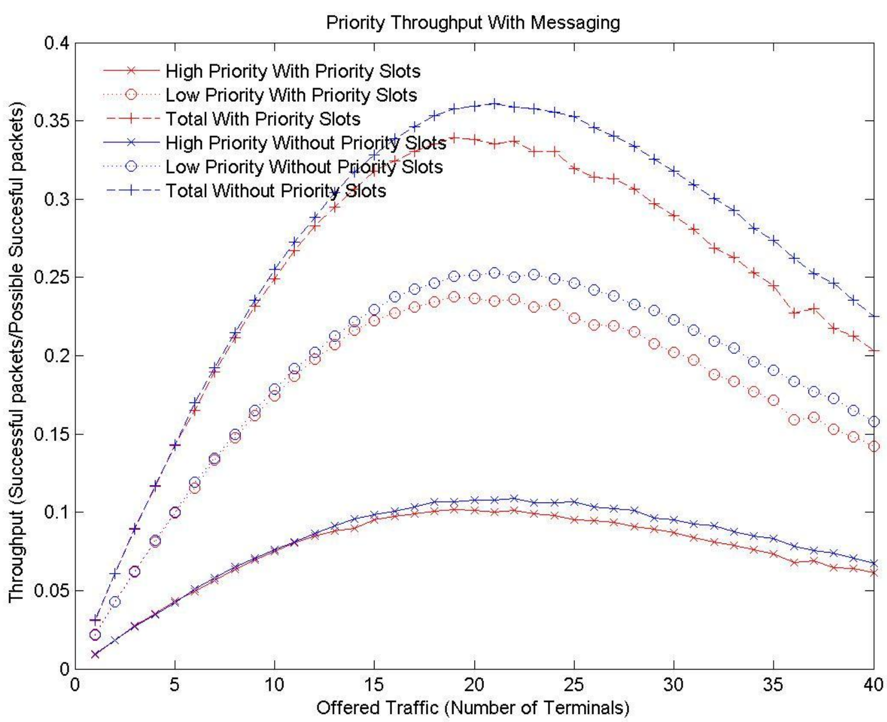


Figure 4.6: Throughput with and without priority slots.

4.7 Summary

The results obtained in this chapter show that the tradeoff between low and high priority delay is acceptable for lower numbers of high priority slots. This validates the protocol introduced in this chapter as a reasonable solution to the multi-priority problem of the R-ALOHA scheme. Given that the high priority traffic can compete for all the slots and not only high priority slots, we need to keep the number of high priority slots in proportion with high priority traffic being generated. Motivated by this, dynamic slot allocation is introduced next in Chapter 5. With such promising simulation results, we conclude that Priority Reservation ALOHA (PR-ALOHA) scheme provides a good solution for handling and speeding transfer of high priority messages in inter vehicle communication environments.

CHAPTER

5. Dynamic Slot Allocation for PR-ALOHA

5.1 Introduction

In PR-ALOHA, priority is incorporated into the R-ALOHA protocol by allocating certain number of time slots in the frame exclusively for high priority traffic. However, the number of high priority slots and low priority slots remains constant for both high and low traffic. This leads to high throughput for high priority traffic at the expense of lower throughput for low priority traffic, particularly at high traffic rate. This has been shown in Chapter 4. This causes both the throughput and delay performance to be limited and dependent on both the number of terminals and the number of slots available. To resolve these issues, a dynamic slot allocation (DSA) algorithm is introduced in this chapter.

5.2 PR-ALOHA Dynamic Slot Allocation

The number of high priority slots (hps) is assumed to be fixed in PR-ALOHA. Therefore, when low priority traffic increases the throughput decreases and the delay increases. Throughput reduction for a high number of terminals results from unused slots (by the low priority traffic) marked for high priority. To solve this problem, a dynamic slot allocation algorithm is developed to optimize throughput and delay performances by dynamically allocating high priority slots in proportion to the high priority traffic. High priority probability (hpp) is dynamically allocated using

$$hpp = nmp(\frac{hps}{hps_{\max}}) \tag{5.1}$$

where $hps_{\max}$ is the maximum number of slots designated for high priority traffic and nmp is the new message probability that is given by

$$nmp = 1 - e^{-\frac{\tau}{t_g}} \tag{5.2}$$

where τ is the duration of a slot and t_g is the average duration between adjacent messages.

As the traffic increases/decreases the associated high priority traffic also increases/decreases. Therefore, instead of having a constant hps the dynamic slot allocation algorithm will dynamically change the value of hps based on the amount of high priority traffic. In the simulation, the dynamic allocation algorithm for high priority slots is used. This allocation model changes the number of hps dynamically with the number of terminals (*M*). Two different functions are developed and tested. The first one employs an exponentially growing hps as a function of the number of terminals, while the second one employs a bell-shaped function.

5.2.1 hps as an exponential growth function

In this approach, hps changes exponentially with M according to the following relationship:

$$hps = c(1 - e^{-kM}) \tag{5.3}$$

The parameter c is a constant that represents the maximum number of high priority slots and k is the rate of increase in the high priority slots as a function of number of terminals. Figure 5.1 shows a simulation of hps with a fixed saturation level at c equal to 8 slots and variable growth rates for k in (a) and fixed k = 0.125 in (b).

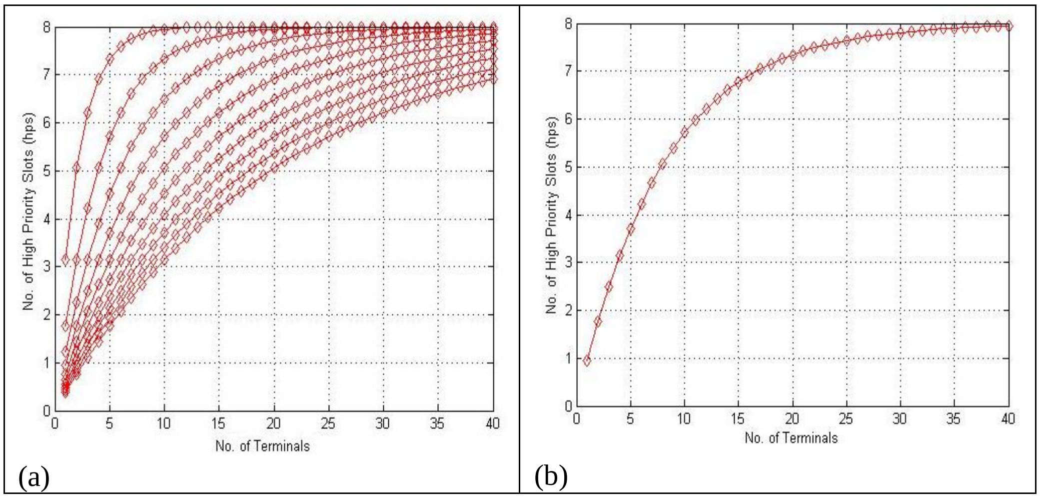


Figure 5.1: hps is plotted as a function of M for variable growth rates k in (a) and fixed k = 0.125 in (b).

5.2.2 *hps* as a bell shaped function

For this approach, hps changes with M following a bell shaped function as given by the following equation:

$$hps = c\,e^{-k(M-a)^2} \tag{5.4}$$

where c is the maximum number of high priority slots which represents the curve's peak (8 slots), a is the mean, and k determines the width of the curve. Figure 5.2 shows a simulation of hps with fixed maximum hps level, c and different widths k in (a) and with fixed k = 0.005 in (b).

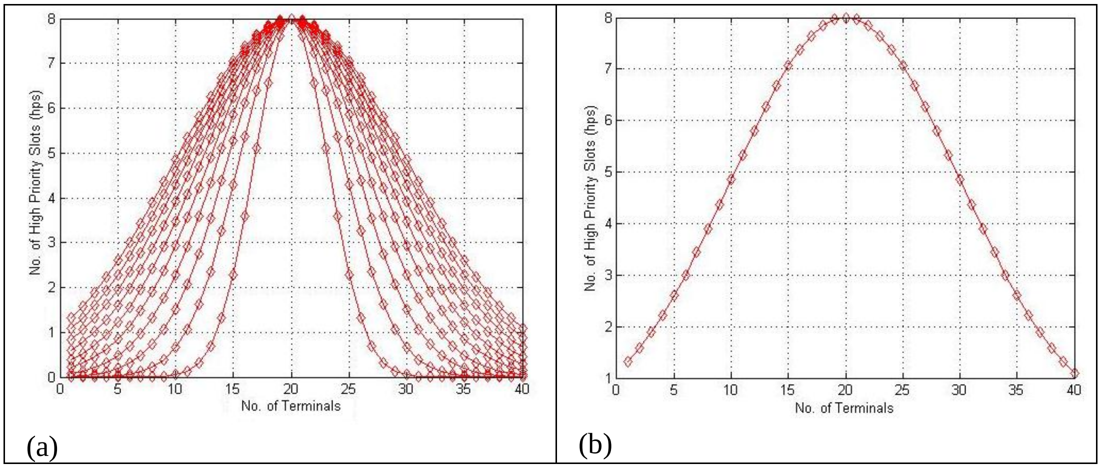
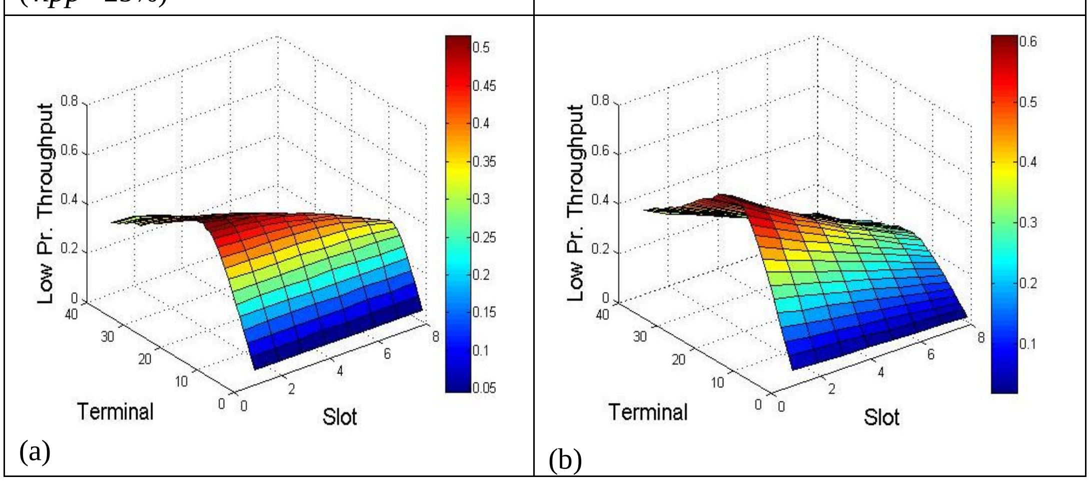


Figure 5.2: Bell shaped *hps* as a function of *M* for variable values of *k* in (a) and for a fixed value of $k = 0.005$ in (b).

5.3 Numerical Results and Discussions

Figures 5.3 and 5.4 show a comparison of low, high and total throughputs and delays without DSA using a fixed high priority probability of 25% and dynamic *hpp*, respectively. The throughput and delay depend significantly on the number of high priority slots and terminals.

Fixed High Priority Probability (*hpp* =25%)	Dynamic High Priority Probability



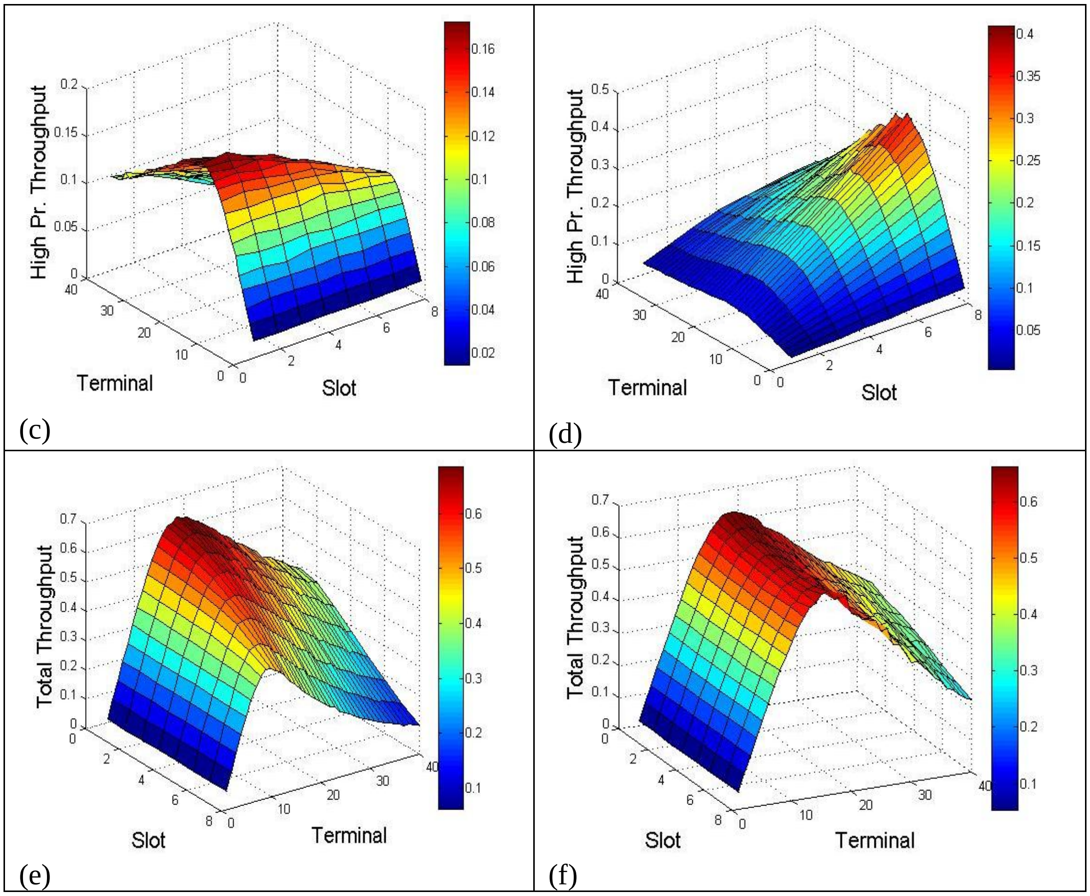


Figure 5.3: Comparison of throughputs and for fixed *hpp* of 25% and dynamic *hpp* ranging between 8%-63% for *hps* 1-8. (a)-(b) show the low priority throughput. (c)-(d) show the high priority throughput. (e)-(f) show the total throughput.

As the traffic increases the throughput increases until it reaches maximum value at nearly 20 terminals and then starts decreasing until it reaches the minimum value at 40 terminals. As shown in Figure 5.3 (left side), the low priority throughput and total throughput decrease as the number of high priority slots increases from 1 to 8 slots. High throughput follows the same pattern. However it is preferred that high throughput increases as the number of high priority slots increases. This is achieved by using a dynamic allocation for the high priority probability. As shown in Figure 5.3 (right side), it is clear that the throughput is higher. Similarly, the delay is lower for high, low and total traffic when using the dynamic *hpp* compared with fixed *hpp* as shown in Figure 5.4.

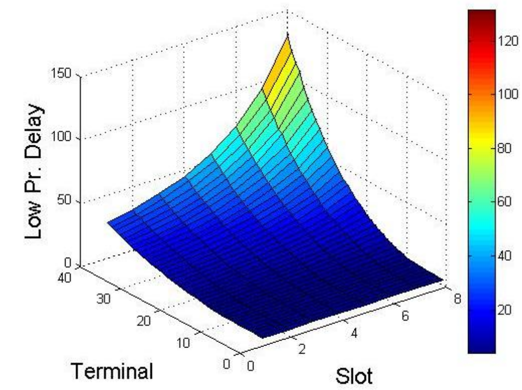
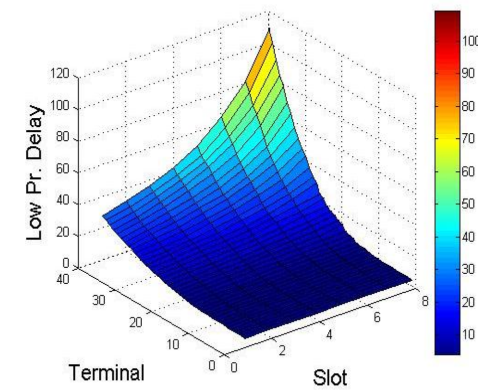
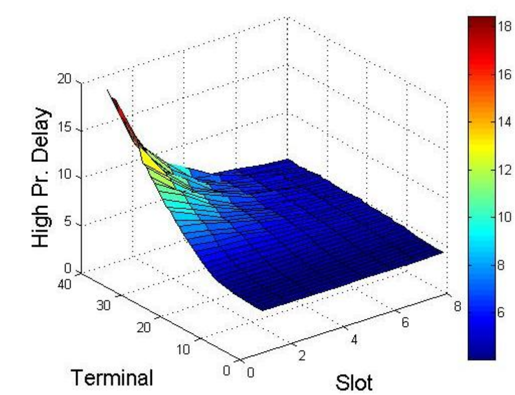
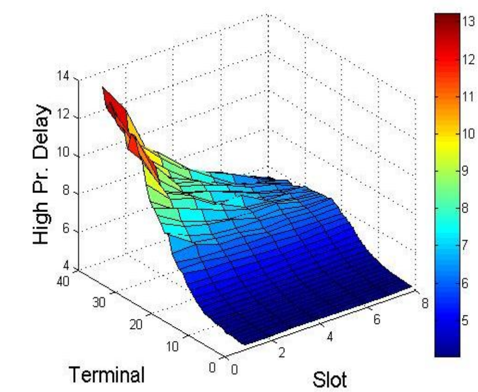
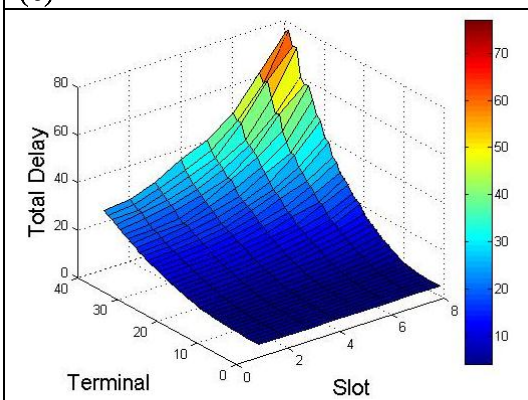
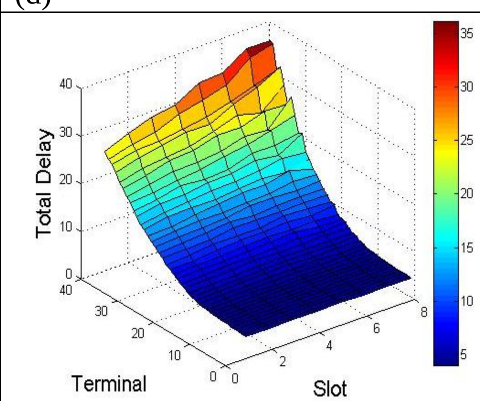
Fixed High Priority Probability (hpp=25%)	Dynamic High Priority Probability
 (a)	 (b)
 (c)	 (d)
 (e)	 (f)

Figure 5.4: Comparison of delay for fixed *hpp* of 25% and dynamic *hpp* ranging between 8%-63% for hps 1-8. (a)-(b) show low priority delay. (c)-(d) show high priority delay. (e)-(f) show total delay.

5.4 High Priority Slots Dynamic Allocation

In order to achieve optimal performance, a dynamically allocated *hps* function is assumed to grow as an exponential growth function with the number of terminal as shown in Figure 5.1. As the number of terminals increases, the number of *hps* increases until it reaches the maximum value of 8 slots. Figure 5.5 illustrates that with the combination of dynamically changing *hpp* and *hps*, the high priority throughput increases significantly and it exceeds the low priority throughput. The total throughput does not seem to be changing by considering a fixed or variable *hpp*. As more slots are allocated for high priority traffic, its delay decreases, while the delay of low priority traffic increases as shown in Figures 5.5 (b)-(d). To optimize the performance with the dynamic allocated *hps*, different values for k in equation (5.3) are tested in order to find the highest throughput and lowest delay. The simulation results show that k =0.125 provides optimal performance over the range of k values that is used in the testing.

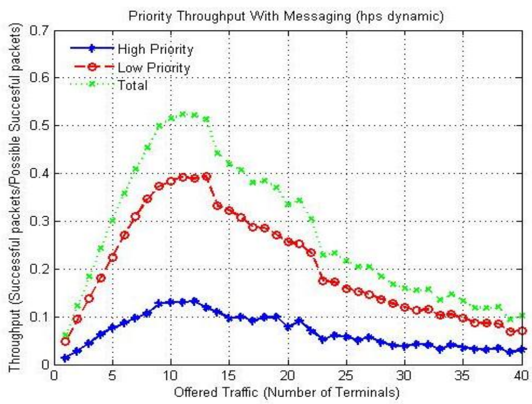
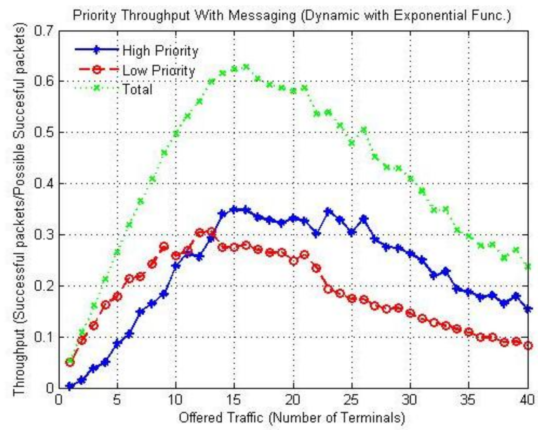
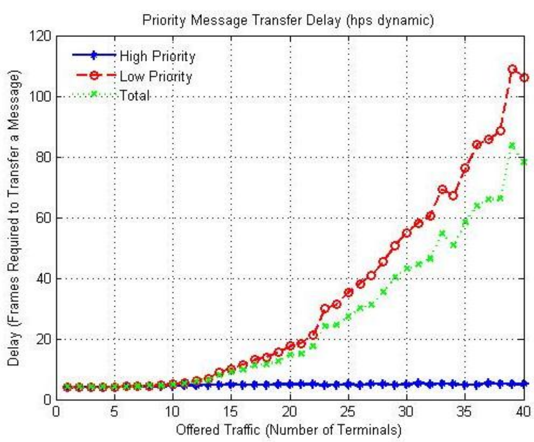
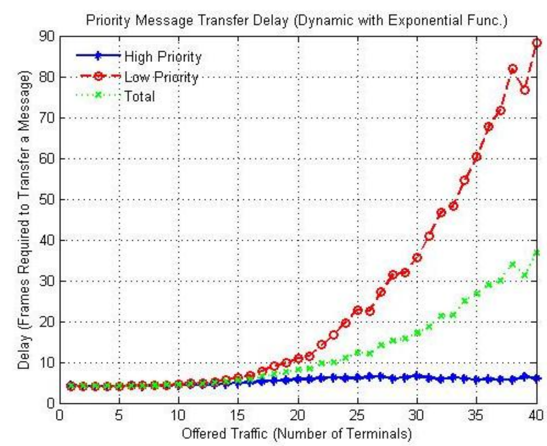
Dynamic hps allocation with exponential function and fixed *hpp* =25%	Dynamic hps allocation with exponential function and dynamic *hpp*
 (a)	 (c)
 (b)	 (d)

Figure 5.5: Comparison of high, low and total throughput (a-and delay for fixed *hpp* of 25% (a)-(b) and dynamic *hpp* ranging between 8%-63% (c)-(d) using an exponential growth dynamically allocated *hps* function.

Secondly, a bell-shaped function is used to dynamically allocate high priority slots as shown in Figure 5.2. Dynamic slot allocation proves to be advantageous by producing larger throughputs at high traffic for low priority traffic in comparison with fixed allocation of fixed number of slots as shown in Figures 5.6 (a)-(b). Improved throughputs are obtained by allocating smaller number of *hps* when the traffic is high and, thus, it does not block the low priority traffic. The maximum delay always occurs at high traffic (40 terminals) as shown in Figures 5.6 (c)-(d). It seems that the maximum delay is strongly dependent on the traffic rather than the designated number of high priority slots.

Dynamic hps allocation with bell-shaped function and fixed hpp=25%	Dynamic hps allocation with bell-shaped function and dynamic hpp

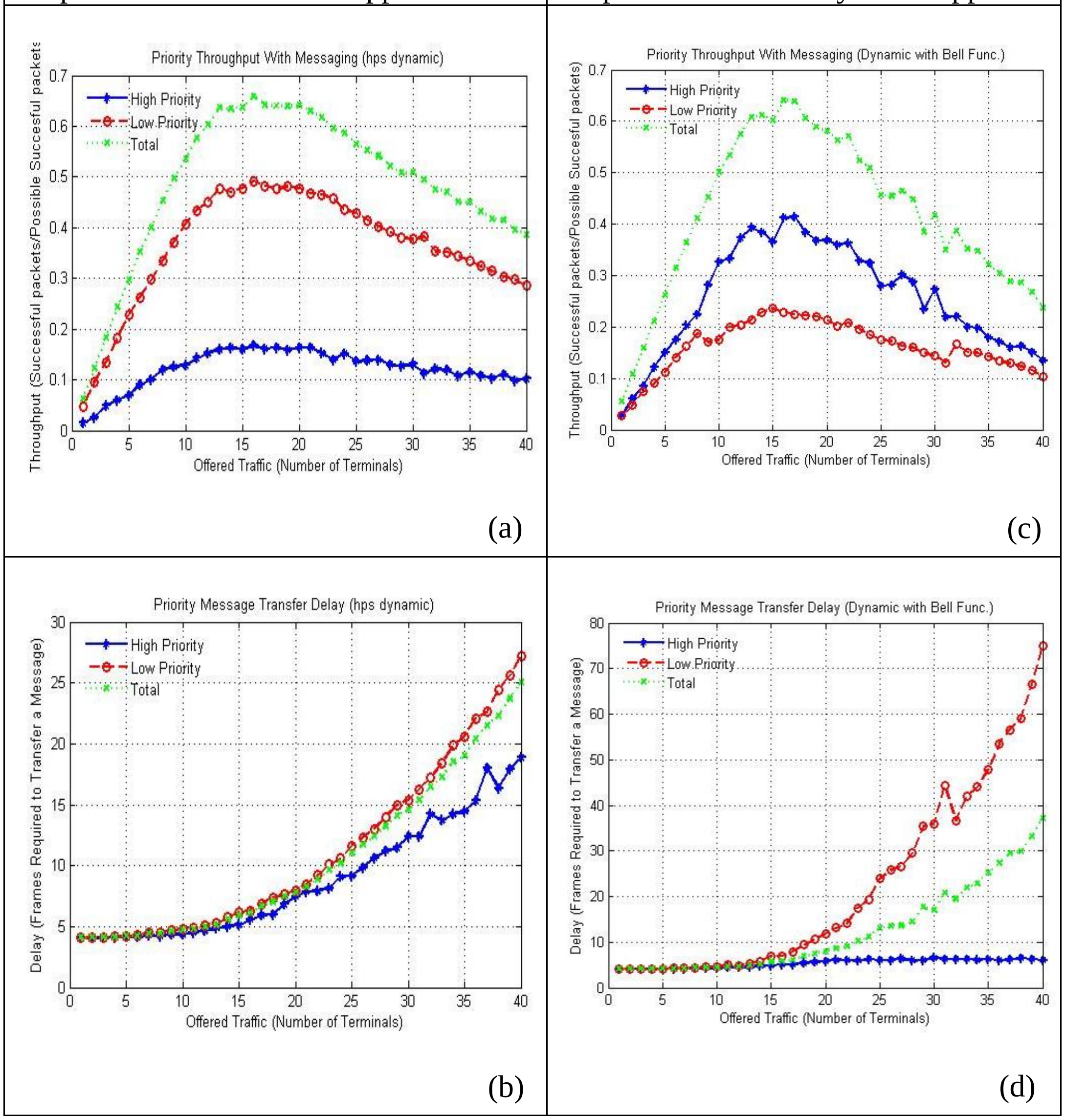


Figure 5.6: Comparison of high, low and total throughput (a-and delay for fixed *hpp* of 25% (a)-(b) and dynamic *hpp* ranging between 8%-63% (c)-(d) using a bell-shaped dynamically allocated *hps* function.

The performance of the dynamic slots allocation model is optimized by testing different values of (a, k) in equation (5.4). The simulation is performed with different values of k (the parameter that controls the width of the bell shape) as shown in Figure 5.2. A wide range of values for k from 0.0001 to 0.2 is tested and the maximum throughput and minimum delay are obtained at $k = 0.0002$ and $a = 20$.

A summary of the high, low and total throughputs and delays with and without DSA for both fixed *hpp* and dynamic *hpp* is shown in the following tables for low (10) and high (40) traffic. Tables 5.1 and 5.2 summarize the throughput for fixed and dynamic *hpp*, respectively. Tables 5.3 and 5.4 summarize the delay for fixed and dynamic *hpp*, respectively. Each table lists the data summary for four cases: fixed high priority slots of 4, fixed high priority slots of 8, dynamic slot allocation using exponential function, and dynamic slot allocation using bell-shaped function. For fixed *hpp*, the bell-shaped DSA gives the best performance compared with fixed and exponential *hps*. In contrast, with dynamic *hpp*, the best performance is obtained with exponential DSA.

TABLE 5.1: Summary of the throughput at low and high traffic for fixed *hpp*=25%

	High Priority Throughput		Low Priority Throughput		Total Throughput	
	Low M=10	High M=40	Low M=10	High M=40	Low M=10	High M=40
hps = 4	14%	10%	42%	20%	56%	30%
hps = 8	10%	3%	34%	8%	44%	11%
Expo. DSA	14%	4%	39%	8%	53%	10%
Bell DSA	14%	10%	41%	30%	55%	40%

TABLE 5.2: Summary of the throughput at low and high traffic for dynamic *hpp*

	High Priority Throughput		Low Priority Throughput		Total Throughput	
	Low M=10	High M=40	Low M =10	High =40	Low M=10	High M=40
hps = 4	25%	16%	27%	9%	50%	25%
hps = 8	34%	14%	18%	10%	50%	24%
Expo. DSA	16%	10%	34%	22%	50%	32%
Bell DSA	34%	17%	18%	9%	50%	26%

TABLE 5.3: Summary of the delay at low and high traffic for fixed *hpp* =25%

	High Priority Delay		Low Priority Delay		Total Priority Delay	
	Low M=10	High M=40	Low M =10	High =40	Low M =10	High =40
hps = 4	5%	8%	5%	34%	5%	42%
hps = 8	5%	5%	5%	100%	5%	79%
Expo. DSA	5%	5%	5%	108%	5%	80%
Bell DSA	5%	18%	5%	27%	5%	25%

TABLE 5.4: Summary of the delay at low and high traffic for dynamic *hpp*

	High Priority Delay		Low Priority Delay		Total Priority Delay	
	Low M=10	High M=40	Low M =10	Low M=10	Low M =10	High =40
hps = 4	5%	8%	5%	88%	5%	38%
hps = 8	4%	7%	4%	75%	4%	38%
Expo. DSA	5%	7%	5%	39%	5%	30%
Bell DSA	5%	6%	5%	82%	5%	34%

5.5 Summary

With PR-ALOHA, high priority traffic is allowed to compete for all the slots and not only high priority slots and, thus, it generally has a lower delay. However, the delay of low priority traffic increases at high traffic because low priority traffic is not allowed to use high priority slots reserved only for high priority traffic. The dynamic allocation model introduced in this chapter for allocating high priority slots based on the available traffic provides a solution by dynamically varying the number of high priority slots as the traffic and high priority probability messages increases. Beyond a certain threshold as the traffic increases, the number of high priority slots can be limited or decreased by the dynamic PR-ALOHA in order to give low priority traffic higher chances of transmitting. The simulation results indicate that PR-ALOHA with dynamic slot allocation provides a good solution to obtain controllable throughput and delay for priority traffic in the inter vehicle communications world.

CHAPTER

6. MARKOV MODELING WITH ANALYSIS AND EVALUATION OF PR-ALOHA

6.1 Introduction

In this chapter, a two-dimensional Markov model of the PR-ALOHA protocol, coupled with Monte Carlo simulation, is introduced to investigate the dynamic behavior of PR-ALOHA in the transient state. The performance parameters of PR-ALOHA in an IVC environment, as measured by its throughput, packet delivery ratio and packet drop rate (PDR) in steady state, are investigated and a comparison with regular R-ALOHA is also carried out.

6.2 System Description

6.2.1 Inter Vehicle Communication (IVC) Environment

IVC is considered a promising solution for improving traffic safety, reducing congestion and increasing environmental efficiency of transportation systems [109-111]. In IVC, the communications among vehicles are achieved by direct transmission of information among nearby vehicles without the use of a fixed infrastructure. Each vehicle (or terminal) is self-organized and together they form a decentralized mobile network. Vehicles move on predetermined roads, typically following predefined mobility patterns. Moreover, it is often possible for a vehicle to get its geographical position using the Global Positioning System (GPS). There are two types of communications in IVC that include single-hop and multi-hop. In single-hop communications, a terminal communicates with its neighbors to advise them of an event such as braking or accident. In multi-hop communications, a terminal communicates with other terminals on the street to obtain information about certain services or to disseminate information. With PR-ALOHA protocol, these two types of communications may be considered as high priority single-hop and normal (or low) priority multi-hop.

6.2.2 PR-ALOHA Protocol for Wireless Communications

PR-ALOHA is a two-level priority MAC protocol that utilizes a single channel. The channel is divided into frames, where each frame is further divided into N slots. A pre-specified percentage P_{hps} of the channel slots are assigned to be high priority slots, while the remaining percentage P_{lps} of the channel slots are considered low priority slots. The high priority slots are reserved exclusively for high priority terminals, and a high priority terminal may contend for any empty slot, including those slots not reserved for high priority as shown in Figure 6.1. In contrast, a normal (low) priority terminal may contend only for the N_l low priority slots, i.e., those labeled L in Figure 6.1. This mechanism effectively increases the number of slots that a high priority terminal may compete for and thus decreases delays in high priority messages.

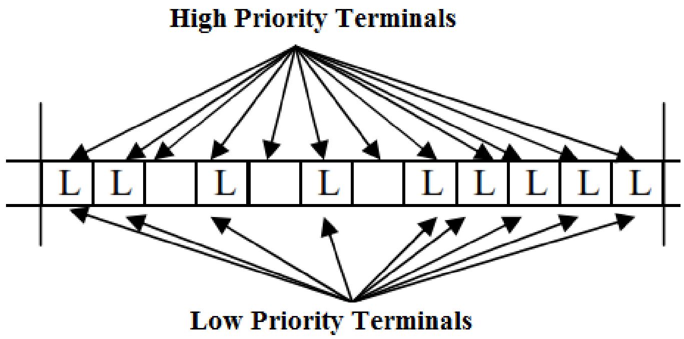


Figure 6.1: Frame architecture of PR-ALOHA.

Note that no preference is granted to high priority terminals when high and low priority terminals contend for the same slot. Instead, a collision occurs and the slot is neither accessed nor reserved. Table 6.1 summarizes the variables used throughout the analysis.

TABLE 6.1: List of Variables and Their Meanings

Variable	**Meaning**
P_{hps}	Percentage of high priority slots relative to the total number of slots
P_{lps}	Percentage of low priority slots relative to the total number of slots
N	Total number of slots in a frame
N_l	Number of slots marked as low priority L, see Figure (1)
M	Total number of terminals (high and low priority)
M_h	Number of high priority terminals
M_l	Number of low priority terminals
hpp	High priority probability, i.e., $M_h = hpp \bullet M$
lpp	Low priority probability, i.e., $M_l = lpp \bullet M$
nmp	New message probability

6.3 Markov Modeling of the Transient State

Markov analysis has been a preferred method for studying ALOHA-based protocols because of its ability to provide information on the dynamic behavior of the system. Assume that the number of terminals in the network is M and the total number of slots (both high and low priorities) in each frame is N. Also assume that each network terminal has a message to transmit and each message has four packets, where only one packet per frame can be transmitted. In addition, assume that $M \le N_l$, and that the number of network terminals do not change during the reservation process until each terminal has reserved a slot for transmission. High priority traffic M_h and low priority traffic M_l are determined using a pre-specified percentage of high priority probability (hpp) and low priority probability (lpp), e.g., $M_h = hpp \bullet M$. A high priority terminal may choose any slot with a probability ($p = 1/N$), while a low priority terminal may choose only a low priority slot with probability ($p' = 1/N_l$). Given that the impact on the obtained results is minimal, the probability is approximated by $p' = 1/(N \bullet P_{lps})$. Given that there are m contending terminals at the beginning of a frame, let $b[m,i,p]$ be the binomial probability that i out of m terminals will randomly choose a particular slot with probability p:

$$b[m,i,p] = \binom{m}{i} p^i (1-p)^{m-i} \tag{6.1}$$

where $\binom{m}{i} = \frac{m!}{i!(m-i)!}$.

Let $P(k_h, k_l \mid m_h, m_l, n)$ denote the probability of having k_h successful high priority terminals and k_l successful low priority terminals given m_h high priority contending terminals, m_l low priority contending terminals, and n unreserved slots. Each slot can be either an empty slot (not reserved), reserved low priority slot (may be reserved by high or low priority terminals) or reserved high priority slot (may be reserved by high priority terminals only). To calculate the probability $P(k_h, k_l \mid m_h, m_l, n)$, three cases for the number of terminals i in equation (6.1) are considered, namely, $i = 0,\ i = 1,\ and\ i \geq 2$: For $i = 0$, no terminals are competing for the slot and the probability is given by:

$$\begin{aligned} P(k_h, k_l \mid m_h, m_l, n) = {} & P_{lps} \bullet b[m_l, 0, p'] \bullet b[m_h, 0, p] \bullet P(k_h, k_l \mid m_h, m_l, n-1) \\ & + P_{hps} \bullet b[m_h, 0, p] \bullet P(k_h, k_l \mid m_h, m_l, n-1). \end{aligned} \tag{6.2}$$

For $i = 1$, only one terminal is competing for the slot. If the slot is low priority, the competing terminal can be either high priority or low priority. However, if the slot is high priority then the competing terminal can only be a high priority. The probability is given by:

$$\begin{aligned} P(k_h, k_l \mid m_h, m_l, n) = {} & P_{lps} \bullet (b[m_l, 0, p'] \bullet b[m_h, 1, p] \bullet P(k_h - 1, k_l \mid m_h - 1, m_l, n-1) \\ & + b[m_l, 1, p'] \bullet b[m_h, 0, p] \bullet P(k_h, k_l - 1 \mid m_h, m_l - 1, n-1)) \\ & + P_{hps} \bullet b[m_h, 1, p] \bullet P(k_h - 1, k_l \mid m_h - 1, m_l, n-1). \end{aligned} \tag{6.3}$$

For $i \geq 2$, at least two terminals are competing for the slot. If the slot is low priority, there are three possibilities: (a) all competing terminals are high priorities, (b) all competing terminals are low priorities, or (c) there are low and high priority terminals competing for the slot. If the slot is high priority, then all competing terminals can only be high priorities. The probability is given by the following equation:

$$P(k_h,k_l \mid m_h,m_l,n) = P_{lps} \bullet (b[m_l,0,p'] \bullet \sum_{i=2}^{m_h} b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i, m_l, n-1)$$
$$+ b[m_h,0,p] \bullet \sum_{i=2}^{m_l} b[m_l,i,p'] \bullet P(k_h,k_l \mid m_h, m_l - i, n-1)) \qquad (6.4)$$
$$+ P_{lps} \bullet \sum_{j=1}^{m_l} \sum_{i=1}^{m_h} b[m_l,j,p'] \bullet b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i, m_l - j, n-1)$$
$$+ P_{hps} \bullet \sum_{i=2}^{m_h} b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i, m_l, n-1).$$

The probability $P(k_h,k_l \mid m_h,m_l,n)$ may be calculated by combining the terms in (6.2), (6.3) and (6.4) using the following recursive formula:

$$P(k_h,k_l \mid m_h,m_l,n) = P_{lps} \bullet b[m_l,0,p'] \bullet b[m_h,0,p] \bullet P(k_h,k_l \mid m_h,m_l,n-1)$$
$$+ P_{hps} \bullet b[m_h,0,p] \bullet P(k_h,k_l \mid m_h,m_l,n-1)$$

$$+ P_{lps} \bullet (b[m_l,0,p'] \bullet b[m_h,1,p] \bullet P(k_h - 1,k_l \mid m_h - 1,m_l,n-1)$$
$$+ b[m_l,1,p'] \bullet b[m_h,0,p] \bullet P(k_h,k_l - 1 \mid m_h,m_l - 1,n-1))$$
$$+ P_{hps} \bullet b[m_h,1,p] \bullet P(k_h - 1,k_l \mid m_h - 1,m_l,n-1) \qquad (6.5)$$

$$+ P_{lps} \bullet (b[m_l,0,p'] \bullet \sum_{i=2}^{m_h} b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i,m_l,n-1)$$
$$+ b[m_h,0,p] \bullet \sum_{i=2}^{m_l} b[m_l,i,p'] \bullet P(k_h,k_l \mid m_h,m_l - i,n-1))$$
$$+ P_{lps} \bullet \sum_{j=1}^{m_l} \sum_{i=1}^{m_h} b[m_l,j,p'] \bullet b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i,m_l - j,n-1)$$
$$+ P_{hps} \bullet \sum_{i=2}^{m_h} b[m_h,i,p] \bullet P(k_h,k_l \mid m_h - i,m_l,n-1)$$

where

$$\forall\, m_h \in [0, M_h],\ \ \forall\, m_l \in [0, M_l],\ \ \forall\, n \in [1, N]$$
$$\forall\, k_h \in [0, M_h],\ \ \forall\, k_l \in [0, M_l],\ \ m \ge i \ge 2,\quad i \ge j \ge 0$$

Next, let (H_f, L_f) be the number of terminals that successfully reserved slots after the f^{th} frame for high priority terminals and low priority terminals, respectively, for $f = 1, 2, \ldots$. Figure 6.2 shows the two-dimensional Markov model for the PR-ALOHA protocol with an absorbing state (M_{h-1}, M_{l-1}). The state transitions in each step depend only on the direct predecessors where the probability of being in a state at time t depends on the previous state at time $t-1$. In Figure 6.2, for example, being in state (2, 2) at time t depends on being in state (1, 2) or (2, 1) at time $t-1$. The transition between states occurs when a terminal successfully reserves a slot. In each transition, only one terminal is successful in reserving a slot, thus a transition from (1, 2) or (2, 1) to state (2, 2) is allowed. However, a transition from (1, 1) to (2, 2) is not allowed because that means 2 terminals were successful in only one step which is not allowed in the model. Once all high and low priority terminals successfully reserve the slots, the system may be regarded as having achieved stability. The initial probability of i high successful terminals and j low successful terminals after the first frame is given by:

$$Pr(H_1 = i,\ L_1 = j) = P(i, j, M_h, M_l, N) \tag{6.6}$$

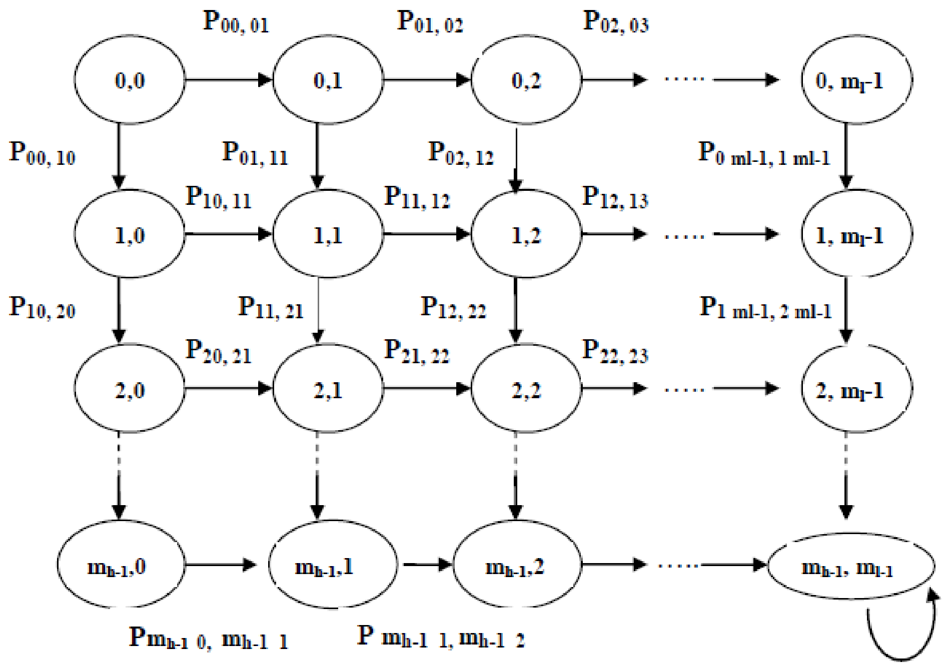


Figure 6.2: Two-dimensional Markov model for the PR-ALOHA protocol

In Figure 6.2, the transition probability $P_{kl,ij}$ between adjacent frames is calculated by the following equation:

$$P_{kl,ij} = Pr((H_f = i, L_f = j) \mid (H_{f\text{-}1} = k, L_{f\text{-}1} = l))$$
$$= \begin{cases} 0, & if \;\; i \le k, \; j \le l, \; i,k \ge M_h, \;\; j,l \ge M_l \\ P(i-k, \; j-l, M_h - i, M_l - j, N - (i+j)), & otherwise \end{cases} \tag{6.7}$$

The probability $Pr(H_f = i, L_f = j)$ of i high successful terminals and j low successful terminals after the f^{th} frame is calculated iteratively by:

$$
\begin{aligned}
&\forall i \in [0, m_l],\ \forall j \in [0, m_h]: \\
&Pr(H_2 = i, L_2 = j) = \sum_{k=0}^{i}\sum_{l=0}^{j} Pr((H_2 = i, L_2 = j) \mid (H_1 = k, L_1 = l)) \bullet \\
&\qquad\qquad Pr(H_1 = k, L_1 = l) \\
&\qquad\qquad \vdots \\
&Pr(H_f = i, L_f = j) = \sum_{k=0}^{i}\sum_{l=0}^{j} Pr((H_f = i, L_f = j) \mid (H_{f-1} = k, L_{f-1} = l)) \bullet \\
&\qquad\qquad Pr(H_{f-1} = k, L_{f-1} = l).
\end{aligned} \tag{6.8}
$$

Assuming that the total number of successful terminals after the f^{th} frame is X_f, and using the marginal distribution of H_f and L_f, the corresponding probabilities are computed by the following equation:

$$
\begin{aligned}
&P(H_f = i) = \sum_{j=0}^{M_l} Pr(H_f = i, L_f = j) \\
&P(L_f = j) = \sum_{i=0}^{M_h} Pr(H_f = i, L_f = j) \\
&P(X_f = k) = \sum_{i=0}^{k} Pr(H_f = k - i, L_f = i),\ \forall k - i \geq 0
\end{aligned} \tag{6.9}
$$

To investigate the speed dependence at which PR-ALOHA achieves network stability upon completing the communication initiation among terminals, the system stabilization time $SST(M, N)$ is defined to be the number of frames elapsed until each terminal in the system reserves successfully a slot [112]. Therefore, the probabilities that the system stabilization time is achieved after the f^{th} frame are:

$$
\begin{aligned}
&Pr(SST_h \leq f) = P(H_f = M_h) \\
&Pr(SST_l \leq f) = P(L_f = M_l) \\
&Pr(SST_t \leq f) = P(X_f = M_h + M_l).
\end{aligned} \tag{6.10}
$$

The distribution of SST is obtained as follows:

$$
\begin{aligned}
Pr(SST_h = f) &= Pr(SST_h \le f) - Pr(SST_h \le f-1) \\
&= P(H_f = M_h) - P(H_{f-1} = M_h)
\end{aligned}
$$

$$
\begin{aligned}
Pr(SST_l = f) &= Pr(SST_l \le f) - Pr(SST_l \le f-1) \\
&= P(L_f = M_l) - P(L_{f-1} = M_l)
\end{aligned} \tag{6.11}
$$

$$
\begin{aligned}
Pr(SST_t = f) &= Pr(SST_t \le f) - Pr(SST_t \le f-1) \\
&= P(X_f = M_h + M_l) - P(X_{f-1} = M_h + M_l).
\end{aligned}
$$

Finally, the average number of successful terminals as a function of the total number of frames is calculated using the following formula:

$$
\begin{aligned}
&\forall f = 1, 2, 3, 4, \ldots.. \\
&A_h(f) = \sum_{k=0}^{M_h} k \;.\; P(H_f = k) \\
&A_l(f) = \sum_{k=0}^{M_l} k \;.\; P(L_f = k) \\
&A_t(f) = \sum_{k=0}^{M_h+M_l} k \;.\; P(X_f = k).
\end{aligned} \tag{6.12}
$$

6.4 Numerical Results and Discussions

Frame-by-frame signaling allows all packets to contend once per frame. This can be achieved by certain frame-by-frame control signaling strategies such as setting an additional slot in each frame or arranging an exclusive signaling channel in the system [105]. In this analysis, a frame-by-frame signaling is used where every terminal in the network is notified of the current reservation status at the beginning of each frame. A Monte Carlo simulation is developed and used to analyze the behavior of PR-ALOHA using the parameters listed in Table 6.2 under the following scenarios:

(a) The total number of terminals in the system is M, and each terminal generates a message consisting of four packets. Each terminal generates one message at a time with a new message probability (nmp) given by:

$$nmp = 1 - e^{-\frac{\tau}{t_g}} \tag{6.13}$$

where τ is the duration of a slot and t_g is the average duration between adjacent messages.

(b) Each packet holds L bits and the frame size is $N = 16$ slots. The simulation is performed from the perspective of one terminal and the system channel is released after a successful message transmission or if a transmission error has occurred. Packet transmission errors, due to multipath and mobility in wireless channels, take place when $\varepsilon + 1$ or more bits are received in error [108]. The packet transmission error probability P_e is calculated by:

$$P_e = \sum_{i=\varepsilon+1}^{L} \binom{L}{i} P_b^i (1 - P_b)^{L-i} \tag{6.14}$$

where P_b is the bit error probability.

(c) At the beginning of each frame, the terminals without messages are given the opportunity to produce a new message. If a terminal has transmitted all four consecutive packets successfully, the message is considered to be transmitted successfully, and the terminal is considered empty again.

TABLE 6.2: System Parameters

Packet size	1024 bits
Bit Error Rate (BER)	0.001
Bit error threshold	3
Data rate	10 Mbps
Packet length	800 bytes
Packets/Message	4
Number of frames in trial	1,000,000 frames
Radius	100 meters
Frame size, N	16 slots
High Priority Probability	33% and 50%
Number of Terminals, M	Varied
Simulation length (slots)	1,000,000 frames= 16,000,000 slots

6.4.1 Performance of PR-ALOHA in Transient State

An important performance parameter of PR-ALOHA is the time needed for terminals to acquire slots in the channel. Figure 6.3 shows both the analytical (dashed lines) and simulation (symbols) results for the average number of terminals that successfully acquire slots as a function of frames for M = 12 with hpp = 33% (Figure 6.3(a)) and hpp = 50% (Figure 6.3(b)). The data in Figure 6.3(a) show that high priority terminals, M_h = 4 reserve their slots within three to four frames, while low priority terminals, M_l = 8 and all terminals, M = 12, reserve their slots within five to six frames. The data in

Figure 6.3(b) demonstrate that high priority terminals, $M_h = 6$, reserve their slots within three to four frames, while low priority terminals, $M_l = 6$, and all terminals, $M = 12$, reserve their slots within four to five frames. Using R-ALOHA, it takes four to five frames for all $M = 12$ terminals to reserve their slots. Introducing priority to R-ALOHA adds a minimal delay of merely one frame for low priority terminals. However, high priority terminals turn out to reserve their slots quickly within three to four frames in both cases. Figure 6.4 shows both the analytical (dashed lines) and simulation (symbols) results for the distribution of SST for $M = 12$ with $hpp = 33\%$ in Figure 6.4(a) and $hpp = 50\%$ in Figure 6.4(b). The probability of all high priority terminals reaching their stable state is highest on the second frame in Figure 6.4(a) and on the third frame in Figure 6.4(b). For both the low priority terminals and the total terminals, the probability is highest on the third and fourth frames in Figure 6.4(a) and on the third frame in Figure 6.4(b). Using R-ALOHA, the probability of slot allocation reaching stable states is highest on the third frame.

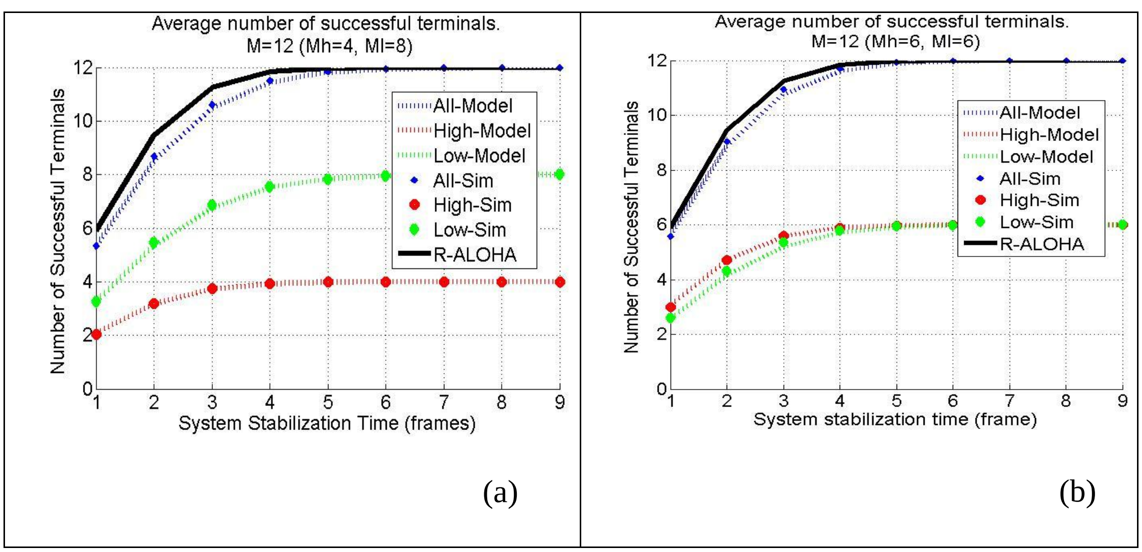


Figure 6.3: Average number of terminals that successfully reserve their slots as a function of the number of frames for M=12 with (a) hpp=0.33 and (b) hpp=0.50. The solid black curve represents the R-ALOHA. The three dashed curves represents the

results of the analytical model, and the three data curves with symbols represent the simulation results for all terminals, high priority terminals and low priority terminals, respectively.

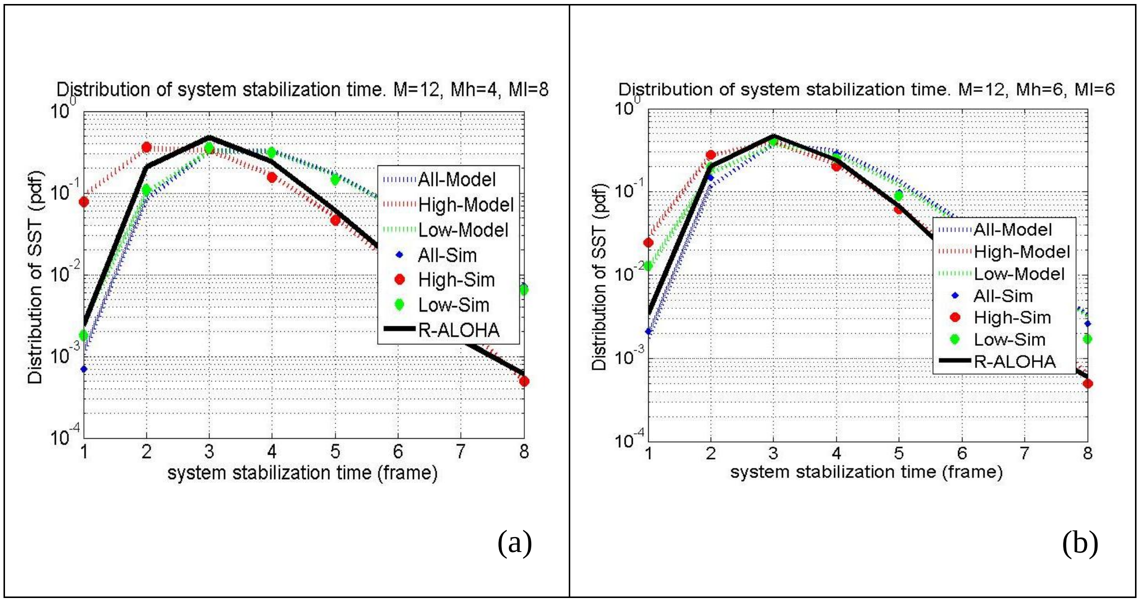


Figure 6.4: The probability distribution of the system stabilization time for *M*=12 with (a) *hpp*=0.33 and (b) *hpp*=0.50. The solid black curve represents the R-ALOHA. The three dashed curves represents the results of the analytical model, and the three data curves with symbols represent the simulation results for all terminals, high priority terminals and low priority terminals, respectively.

6.4.2 Performance of PR-ALOHA in Steady State

Following the transient state, the system enters the steady state which starts when each of the terminals has reserved a time slot in the PR-ALOHA frame. The performance parameters of PR-ALOHA as measured by its packet delivery ratio, system throughput, and packet drop rate in steady state will be represented next.

6.4.2.1 Packet Delivery Ratio

Packet delivery ratio is defined as the ratio of the number of packets that are successfully received to the number of packets that are expected to be received [113]. Figure 6.5 shows the total traffic packet delivery ratio versus the number of terminals.

The number of high priority slots (*hps*) is 25% of the total number of slots (*hps* = 4) and the bit error rate (BER) is 0.001. The results show that the packet delivery ratio decreases when the traffic increases. However, it remains above 96% at 40 terminals. Figure 6.6 demonstrates the packet delivery ratio versus BER ranging from 0.0001 to 0.01 for M=15 in (a) and for different values of M in (b). The packet delivery ratio stays above 96% for BER < 0.005. For BER above 0.005, the packet delivery ratio decreases dramatically, reaching zero around BER of 0.01. The decrease in the packet delivery is due to the delivery failure caused by transmission errors in the channel.

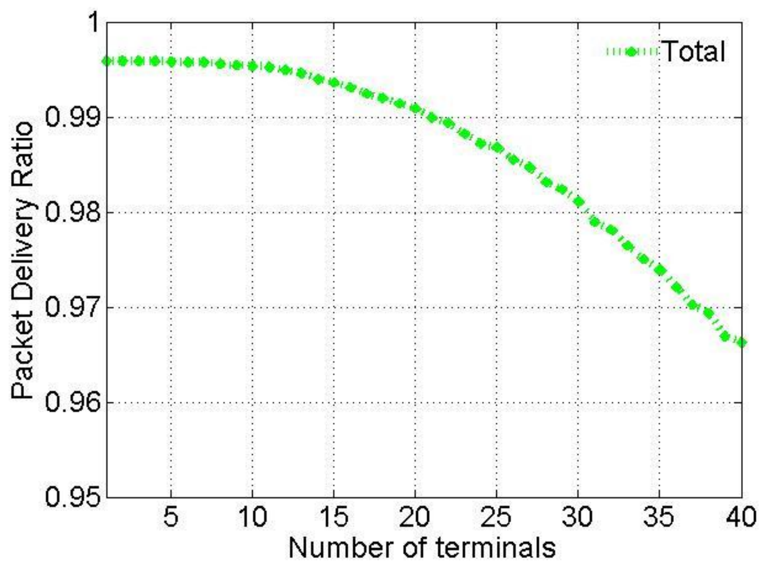


Figure 6.5: Packet delivery ratio of PR-ALOHA for total traffic (low and high priority) versus the number of terminals

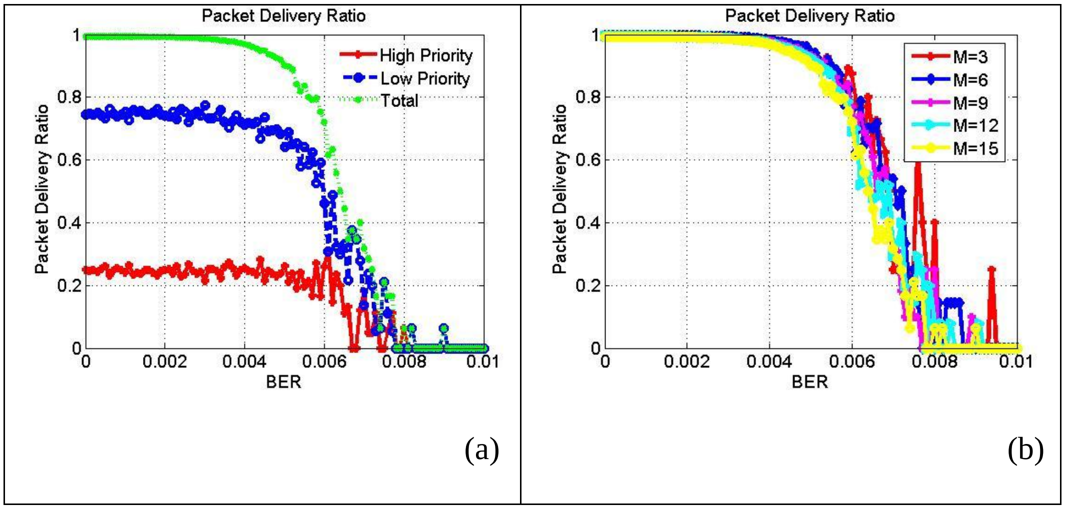


Figure 6.6: Packet delivery ratio of PR-ALOHA for (a) high priority, low priority and total priority at *M*=15, and for (b) total traffic for different *M*.

6.4.2.2 System Throughput

The total throughput is defined as the total number of successfully reserved slots (for both high priority and low priority) to the total number of slots (reserved and free):

$$throughput = \frac{successfully\ reserved\ slots}{total\ number\ of\ slots}$$

$$= 1 - \frac{\text{exp}ected\ free\ slots}{total\ number\ of\ slots} \tag{6.15}$$

Figure 6.7 illustrates the throughput of PR-ALOHA with reference to the number of terminals *M*, for *M* = 1 to 40 terminals, for high priority traffic, low priority traffic and total traffic with a fixed high priority slots of *hps* = 4 and BER = 0.001. In Figure 5.7, as *M* increases from 1 to 16, the throughput increases, reaching a maximum around *M* = 16. Beyond *M* = 16, it decreases until it reaches a minimum at *M* = 40. This behavior can be explained by considering that the terminals are competing for 16 slots only in each frame, *N* = 16. Therefore, when *M* > *N*, more terminals are competing for the same slots and the collision rate is higher, causing the throughput to decrease. Figure 6.8

represents the throughput versus different BER ranging from 0.0001 to 0.01 for M = 15 in (a), and for different values of M in (b). The throughput stays nearly the same for BER < 0.001. When BER exceeds 0.001, the throughput degrades quickly and reaches zero around BER = 0.01.

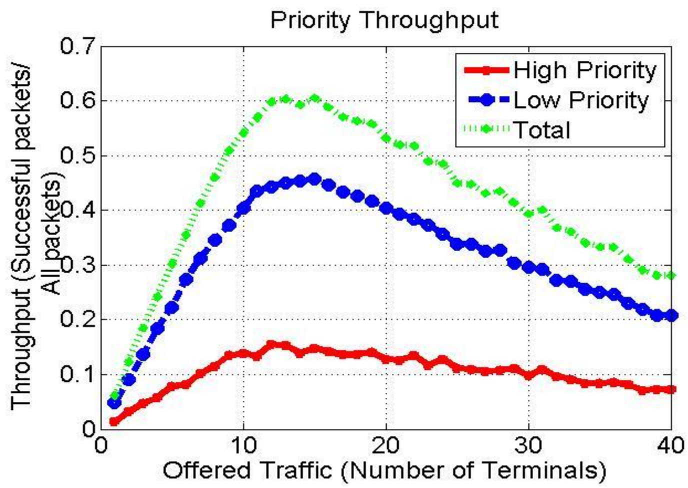


Figure 6.7: Throughput of PR-ALOHA in steady state versus the number of terminals for low priority, high priority and total traffic.

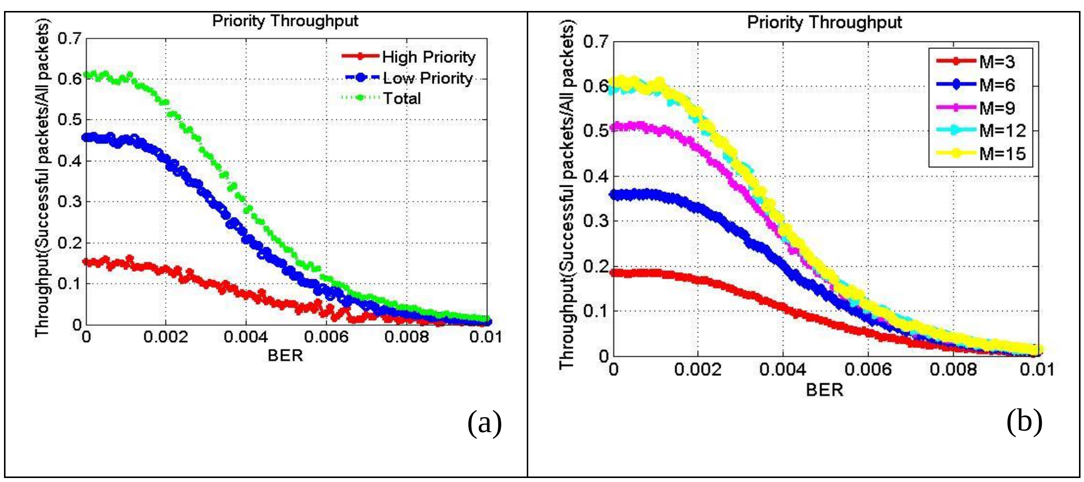


Figure 6.8: Throughput of PR-ALOHA for (a) high priority, low priority and total priority traffic at M=15, and for (b) total traffic with different M.

6.4.2.3 Packet Drop Rate (PDR)

A low packet drop rate is usually a good indicator of the protocol performance. In the analysis below, the packet drop rate is defined as:

$$Packet\ Drop\ Rate = \frac{M - throughput \bullet N}{M}. \qquad (6.16)$$

Figure 6.9 presents the packet drop rate for M = 15 in (a) and for different values of M in (b). The results in Figure 6.9 (b) show that, as the traffic increases from M= 3 to M=15, the packet drop rate increases from 14% to 34% for BER < 0.001. The performance of PDR stays nearly constant for BER < 0.001. When BER exceeds 0.001, the performance degrades quickly and approaches one around BER = 0.01. When PDR reaches one, data are not transmitted and PR-ALOHA stops working.

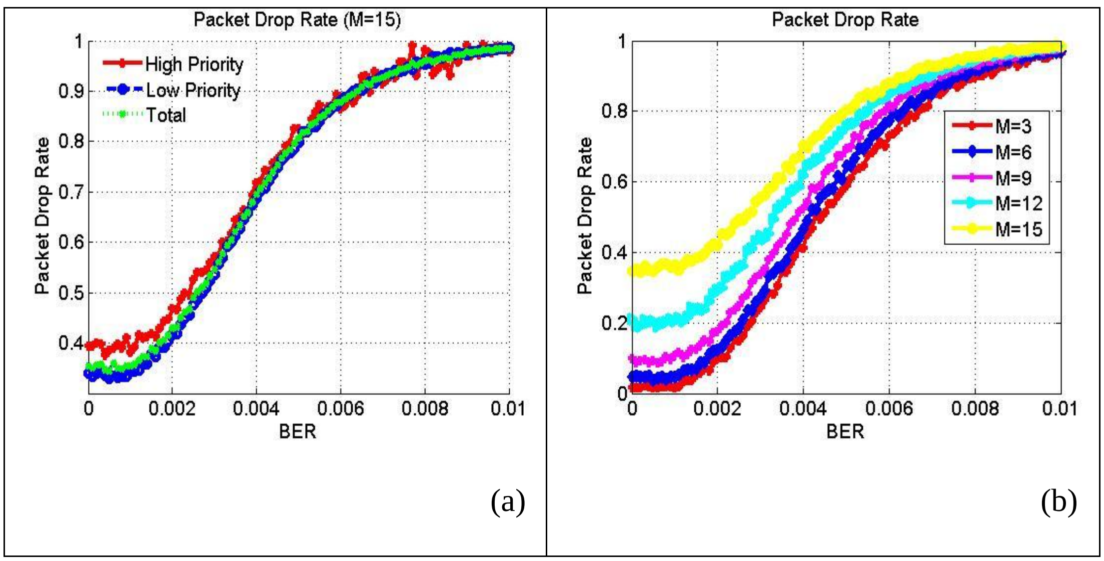


Figure 6.9: Packet drop rate of PR-ALOHA for (a) high priority, low priority and total priority traffic at M=15 and for (b) total traffics for different M.

6.5 Summary

In this chapter, we have presented theoretical analysis of the newly developed PR-ALOHA protocol. The protocol uses the widely-accepted R-ALOHA protocol to offer differentiated services based on traffic priorities. The performance of PR-ALOHA is analyzed using Monte Carlo simulations for both the transient and steady states. The analytical results confirm that by comparing PR-ALOHA with R-ALOHA, terminals with high priority have faster access to the available channel and a higher probability of successfully reserving slots in a shorter amount of time. The simulation results provide validation of the analytical Markov model and verification of the accuracy of the analytical model. The obtained results highlight the potential that PR-ALOHA may be a good candidate for the transmission of high priority messages in VANET environments.

CHAPTER

7. IMPACT OF MOBILITY ON THE PERFORMANCE OF PR-ALOHA PROTOCOL FOR INTER VEHICLE COMMUNICATION ENVIRONMENT

7.1 Introduction

A VANET consists of a group of vehicles (nodes) equipped with wireless devices, the mobility of these nodes is restricted by highway and maximum speed. The mobility of the nodes can be represented by a mobility model which is used to characterize the motion patterns of the mobile nodes and evaluate quantitatively the performance of the network [113-116]. According to [117], mobility models can be categorized into five categories: Traffic models, Flow models, Trace-based models, Behavioral models, and Random models, which are the most popularly used models. There are different Random models such as: Reference Point Group Mobility Model (RPGM) [118, 119], Manhattan Model [120], Freeway Model [121], and Random Way point Model (RWP). The most widely used Random mobility model for the simulation of Mobile Ad Hoc Networks (MANETs) is the RWP model which was presented in several publications [122-125]. In the RWP mobility model, speed and direction are generated randomly, where each node selects a random destination location to move to (i.e., waypoint) with a speed selected from a uniform distribution in the range $[v_{\min}, v_{\max}]$. Once the node reaches the selected location, it pauses for a random time period and then selects another destination with another speed for its next move.

Although RWP mobility model is simple to implement and is the most commonly used, the distributed nature of VANET environment and its constant movement patterns on the roads makes it unrealistic to use a random mobility model to represent the mobility of vehicles on the road. The reasons for that include: vehicles random movement, sharp turns and sudden stops [126]. Several studies [127-129] have explored the impact of mobility models on network performance and found that they significantly affect the protocol performance and delay-capacity trade-offs.

In this chapter, we introduce a practical simple mobility model that is used to analyze the mobility of vehicles on the highway. The impact of mobility on the channel throughput, channel delay and packet drop rate are investigated. Different traffic parameters are considered in our mobility simulation, such as the vehicle speed, vehicle transmission range, road length (as measured by its radius) and the number of vehicles on the road.

7.2 System model

In our mobility model, we consider a unidirectional highway with a single lane forming a closed circular ring road with a radius (R). The number of vehicles on the road is M and each vehicle has a transmission range (r) with $r << R$. The vehicles on the road can communicate directly if the distance between them is no greater than r. While on the highway, each vehicle moves and communicates with other nodes according to the mobility model. In this mobility model, only vehicles moving on a single road are considered in the simulation. This is a valid assumption because the mobility of vehicles on the various roads of a whole network usually follows similar patterns. The moving vehicles are combined to create the VANET scenario shown in Figure 7.1.

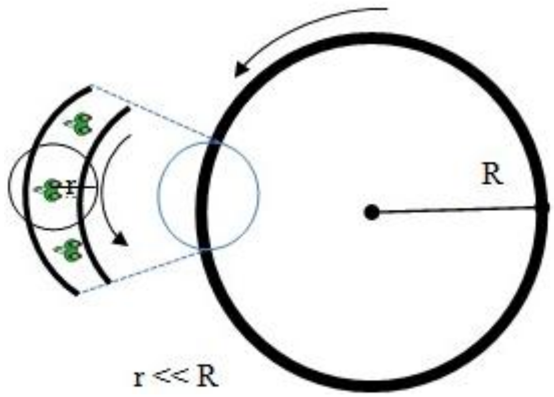


Figure 7.1: Schematic of the VANETs System Used in Simulation

Although in reality nodes on the highway change their speeds, studies [130, 131] showed that the speed of different nodes on the highway usually follows a Gaussian distribution. In our mobility model, each node i moving on the highway is assumed to maintain a constant speed v_i, while the different nodes may have different speeds $v_1, v_2, ..., v_M$ that are independent and randomly distributed. Thus, the velocity distribution can be represented by a Gaussian distribution with a mean speed μ and variance σ^2. The probability density function (pdf) is then given by the following equation:

$$f(v) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(v-\mu)^2}{2\sigma^2}} \tag{7.1}$$

For simplicity, in the simulation the Gaussian distribution of the node speeds is truncated to a minimum speed $v_{\min} = \mu - 3\sigma$ and maximum speed $v_{\max} = \mu + 3\sigma$ which covers 99.7% of all speed values. Furthermore, we assume that $\mu - 3\sigma > 0$ such that only nodes with positive speeds v_i are considered in the simulation.

7.3 Mobility model

Assume that M vehicles are moving on the circular road as explained previously. In addition, suppose that each vehicle i has a transmission range r and is moving on the road with a constant speed v_i that is obtained from the truncated Gaussian distribution. Let φ_i be the polar angle which vehicle i makes with the X-axis as shown in Figure 7.2, where φ_i is between 0 and 2π. Also, let θ be the transmission range measured in terms of angle as shown in Figure 7.2, which we will refer to in the sequel simply as *transmission angle*.

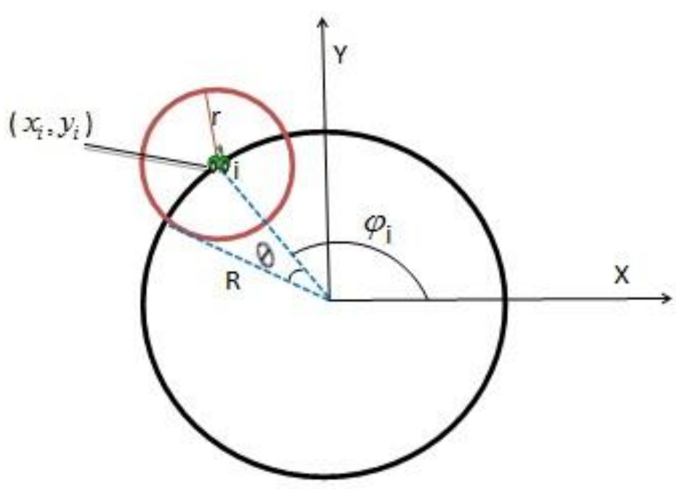


Figure 7.2: Mobility Model

The Cartesian (x_i, y_i) position of each vehicle i on the road is given by the following equation:

$$x_i = R\cos(\varphi_i)$$
$$y_i = R\sin(\varphi_i) \tag{7.2}$$

Two vehicles i and j at positions (x_i, y_i) and (x_j, y_j), respectively, can communicate with each other if their polar angular difference is not greater than θ, or equivalently, the difference in their positions satisfies

$$\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \leq r \tag{7.3}$$

If r is the chord length of the circle as shown in Figure 7.3, then from the geometrical relations, the relationship between angle θ , r and R is obtained to be

$$\sin\left(\frac{\theta}{2}\right) = \frac{r}{2R} \tag{7.4}$$

$$\theta = 2\sin^{-1}\left(\frac{r}{2R}\right) \tag{7.5}$$

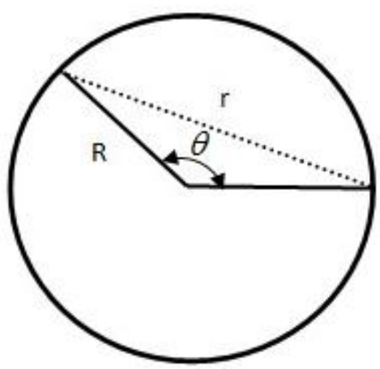


Figure 7.3: Relation of angle θ with r and R .

In the simulation process, we used a discrete time model where the angular position φ_i of each vehicle i is updated every T seconds according to equation (7.6), where t denotes time. That is,

$$\varphi_i(t+T) = \varphi_i(t) + \frac{T}{R} \ . \ v_i \tag{7.6}$$

which can also be written and interpreted as

$$v_i = \frac{\text{distance}}{\text{time}} = \frac{\Delta\varphi \bullet R}{T}$$

where

$$\Delta\varphi = \varphi_i(t+T) - \varphi_i(t)$$

.

Next, we present analytical formulas used for throughput and packet drop rate followed by analytical expressions that can be used to calculate the average number of vehicles and vehicle density on the highway.

7.3.1 Throughput

Throughput is defined to be the total number of successfully reserved slots (for both high priority and low priority vehicles) divided by the total number of available slots (including reserved and unreserved (free)) as given by the following equation:

$$throughput = \frac{successfully\ reserved\ slots}{total\ number\ of\ slots}$$

$$= 1 - \frac{expected\ free\ slots}{total\ number\ of\ slots} \tag{7.7}$$

7.3.2 Packet Drop Rate

A low packet drop rate is usually a good representative parameter of the protocol performance. In our analysis, packet drop rate is defined as follows:

$$Packet\ Drop\ Rate = \frac{M - throughput.N}{M} \tag{7.8}$$

7.3.3 Average number of vehicles on the road

Using steady state analysis, the average number of vehicles M located on the highway of length L, with only *one stream* of vehicles and an arrival rate of λ, can be calculated using the following formula:

$$M = \frac{L\lambda}{\mu} \tag{7.9}$$

where μ is the average speed of the vehicles on the highway.

7.3.4 Vehicle density

The vehicle density is typically measured in terms of vehicles/kilometer/lane (veh / km / ln) and is considered an important parameter in measuring vehicle mobility. Let us consider a highway with one lane and an uninterrupted flow (e.g., no stop signs and no traffic signals). Then, the vehicle density per unit distance is defined to be [132]:

$$k = \frac{n_l}{l} \tag{7.10}$$

where k is the traffic density measured in vehicles per unit distance, n_l is the number of vehicles occupying a certain length of the highway at a certain time, and l is the length of the highway segment. Once the values of the vehicle density per unit distance, k, and speed v, are determined according to predefined conditions, the traffic flow can be calculated by:

$$q = vk \tag{7.11}$$

where q is the traffic flow, in vehicles per unit time.

The speed-density relationship in equation (7.11) is linear with a negative slope. Therefore, as the number of vehicles on the road increases, the density increases and the speed of the vehicles on the highway decreases until it reaches zero when the density equals the jam density. For simplicity, in our analysis we assume that the vehicle speeds, $v_1, v_2, \ldots, v_M$,are independent of the density. The vehicle density is an important parameter in the study of system throughput and delay. The relationship between the number of vehicles on the road and throughput, delay and packet drop rate are investigated by simulation in this work.

7.4 Simulation setup

Monte Carlo simulation using MatLab® coding is used to investigate the effect of mobility on the performance of PR-ALOHA protocol in a mobile environment. Parameters such as road radius, vehicle transmission range and the number of vehicles on the road are changed to see their effect on the system throughput, system delay and system packet drop rate. The simulation length is 1,000,000 frames. The mobile vehicles followed the mobility model as discussed previously. A frame-by-frame signaling is used where each vehicle in the network is notified with the current positions of the surrounding vehicles and the reservation slot status at the beginning of every frame. The number of vehicles on the road is assumed to be *M*, and each vehicle generates a message consisting of four packets. Each vehicle can generate only one message at a time. The new message probability (*nmp*) is calculated using the following equation:

$$nmp = 1 - e^{-\frac{\tau}{t_g}} \tag{7.12}$$

where τ is the duration of a slot and t_g is the average duration between adjacent messages. If a node wants to transmit its data, two conditions must be satisfied. First, the node must be in transmitting mode, i.e. a node cannot be TX and RX at the same time. Second, the node must find a receiver within its transmission range. The system parameters used in the simulation and their units are listed in Table 7.1.

TABLE 7.1: System Parameters and Their Units

Parameter	***Unit***
Number of vehicles, M	Vehicles
Highway radius, R	Miles
Vehicle transmission range, r	Miles
Vehicle speed, v	Miles/Hour
Average speed, μ	Miles/Hour
Standard deviation, σ	Miles/Hour
Traffic density in vehicles per unit distance, k	Vehicles/Mile
Traffic flow, q	Vehicles/Second

7.5 Numerical results and discussions

Figure 7.4 shows the resulting throughput as a function of the number of terminals for different t_g values and a frame size of N = 16 slots. The results shows that for small number of terminals, i.e. M = 10, as t_g values increase from 1 to 4 the throughput decreases from 0.55 to 0.38. The throughput is nearly equal for all t_g values when the number of terminals reaches a value equal to the number of slots in the frame (N = 16). As the number of terminals, M , increases beyond N , i.e. M = 25, the throughput increases from 0.47 to 0.54 for t_g from 1 to 4. This behavior can be explained by considering that, if the number of terminals is smaller than the number of the slots in the frame, then the throughput is higher for a high rate of message generation. At every frame there are higher possibilities for the new generated message to reserve a slot. However, when the number of terminals is greater than the number of slots, larger number of terminals are competing, causing collisions to occur. Thus, a high message generation rate will make it worse and ultimately decrease the throughput. For M = 25, the throughput is highest when t_g = 4, where a message is generated every four frames compared to t_g = 1 where a message is generated every one frame.

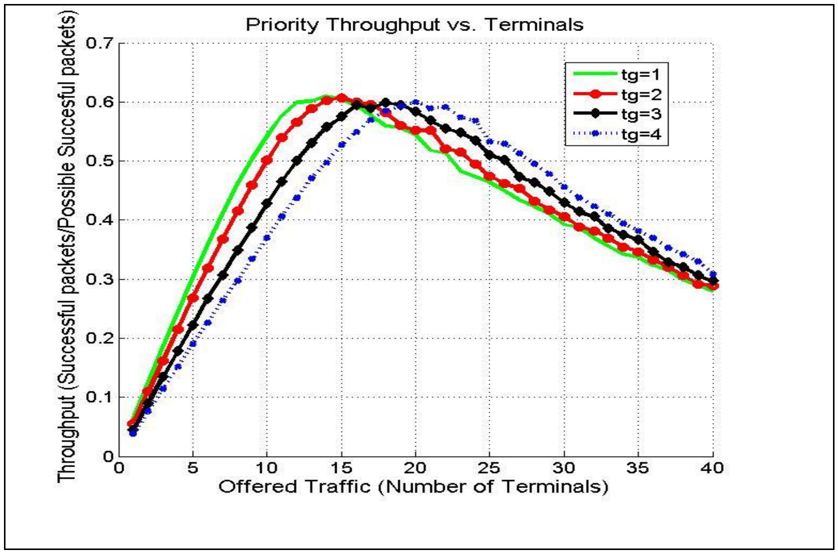


Figure 7.4: Throughput as a function of the number of terminals for different t_g values and a frame size of N = 16 slots.

Figure 7.5 shows the delay versus the number of terminals for different average duration between adjacent messages, t_g. The results show that for a small M, the delay is not sensitive to variations in t_g and is nearly flat. As the number of terminals increases and reaches the number of slots (N = 16), the faster the messages are generated the higher the delays. For example in Figure 7.5 for M = 20, the delay increases from 6 to10 frames as t_g decreases from 4 to1.

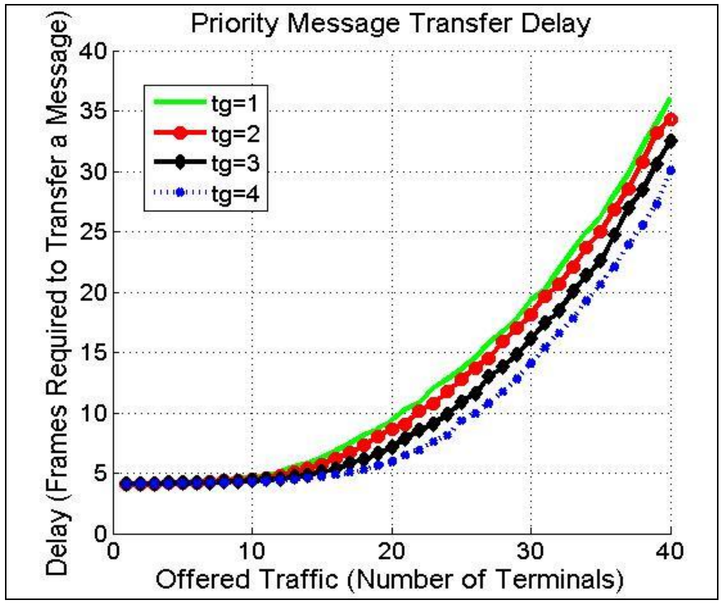


Figure 7.5: Delay vs. Number of terminals for different t_g values with frame size N=16.

To investigate the effect of mobility on the performance parameters, including the throughput, delay, and packet drop rate in our PR-ALOHA protocol, a variable number of vehicles, M, ranging from 100 to 500, are simulated with N = 160 and *hps* = 40. The simulation is performed for high priority terminals, low priority terminals and for total terminals using varying road radius R (see Figure 7.1 for definition) ranging from 1 to 10 miles as shown in Figure 7.6, variable vehicle transmission range r ranging from 0.2 to 1 mile as shown in Figure 7.7, and variable packet error rate for 100 values ranging from (0 – 0.96) for bit error rate BER = (0:0.001:0.01) as shown in Figure 7.8.

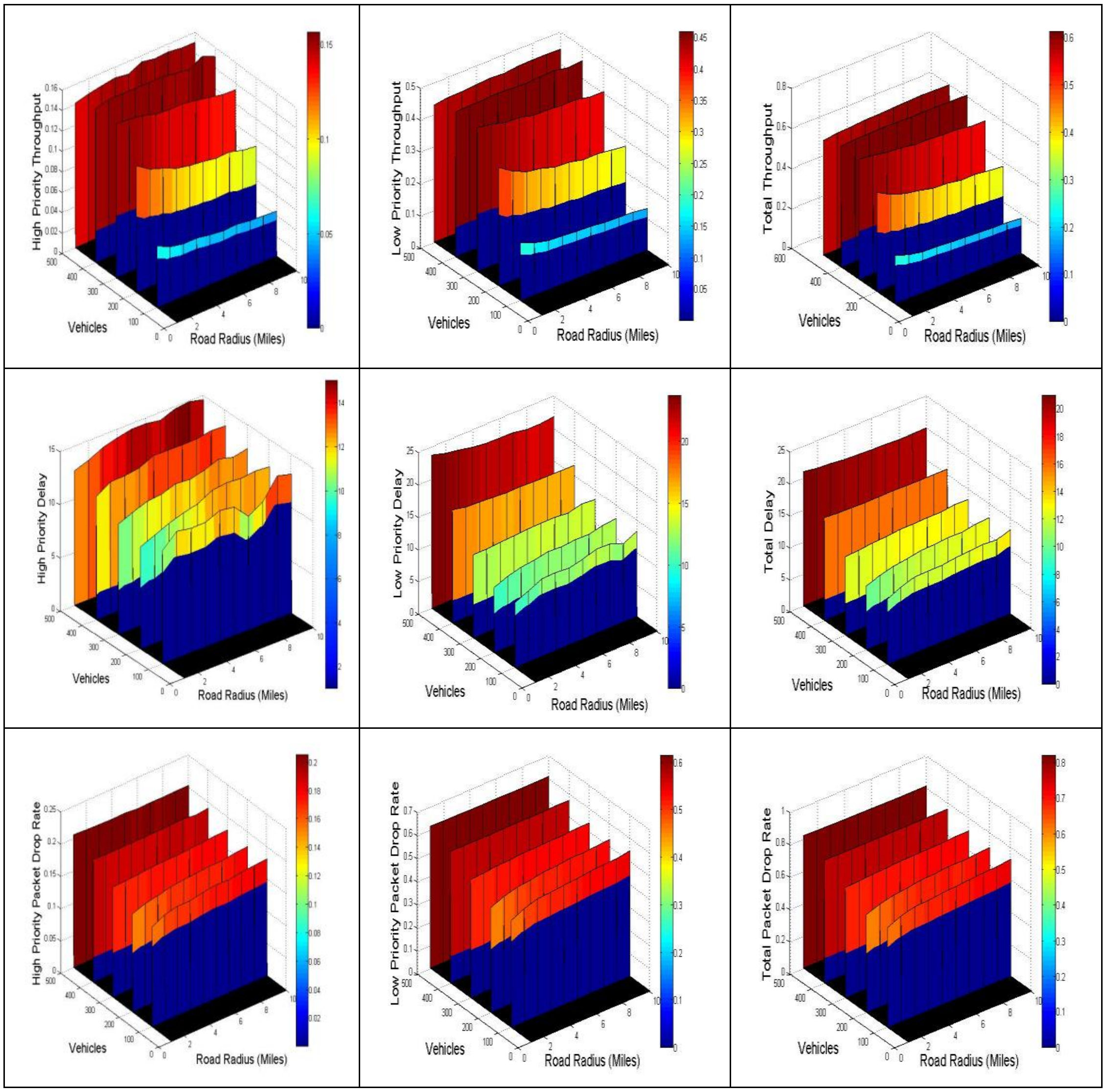


Figure 7.6: Throughput, delay and packet drop rate with variable road radius and vehicles number for (vehicle transmission range $r = 0.4$ miles) with a frame size of $N = 160$ slots.

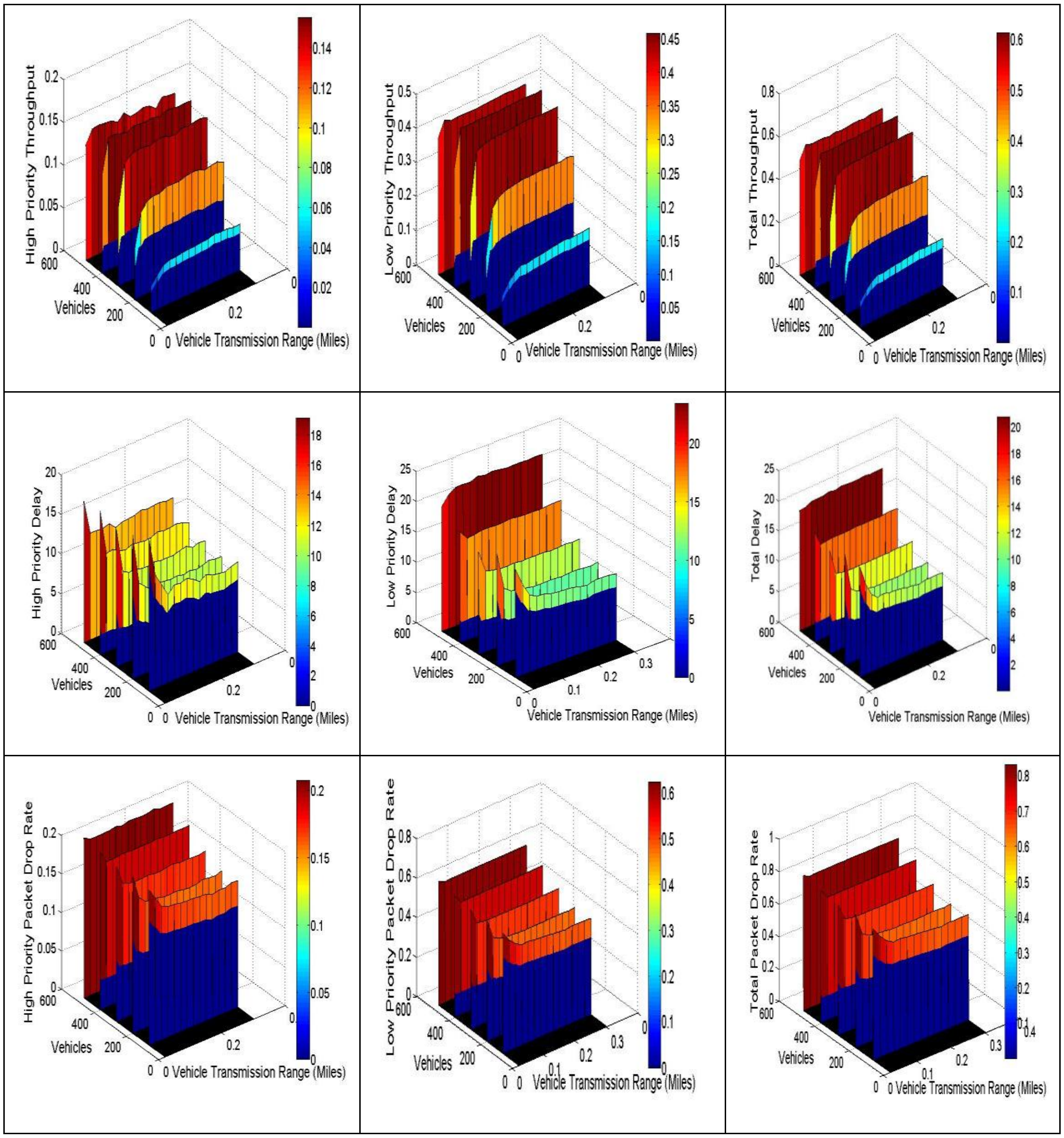


Figure 7.7: Throughput, delay and packet drop rate with variable vehicle transmission range and vehicles number for (road radius $R = 2$ miles) with a frame size of $N = 160$ slots.

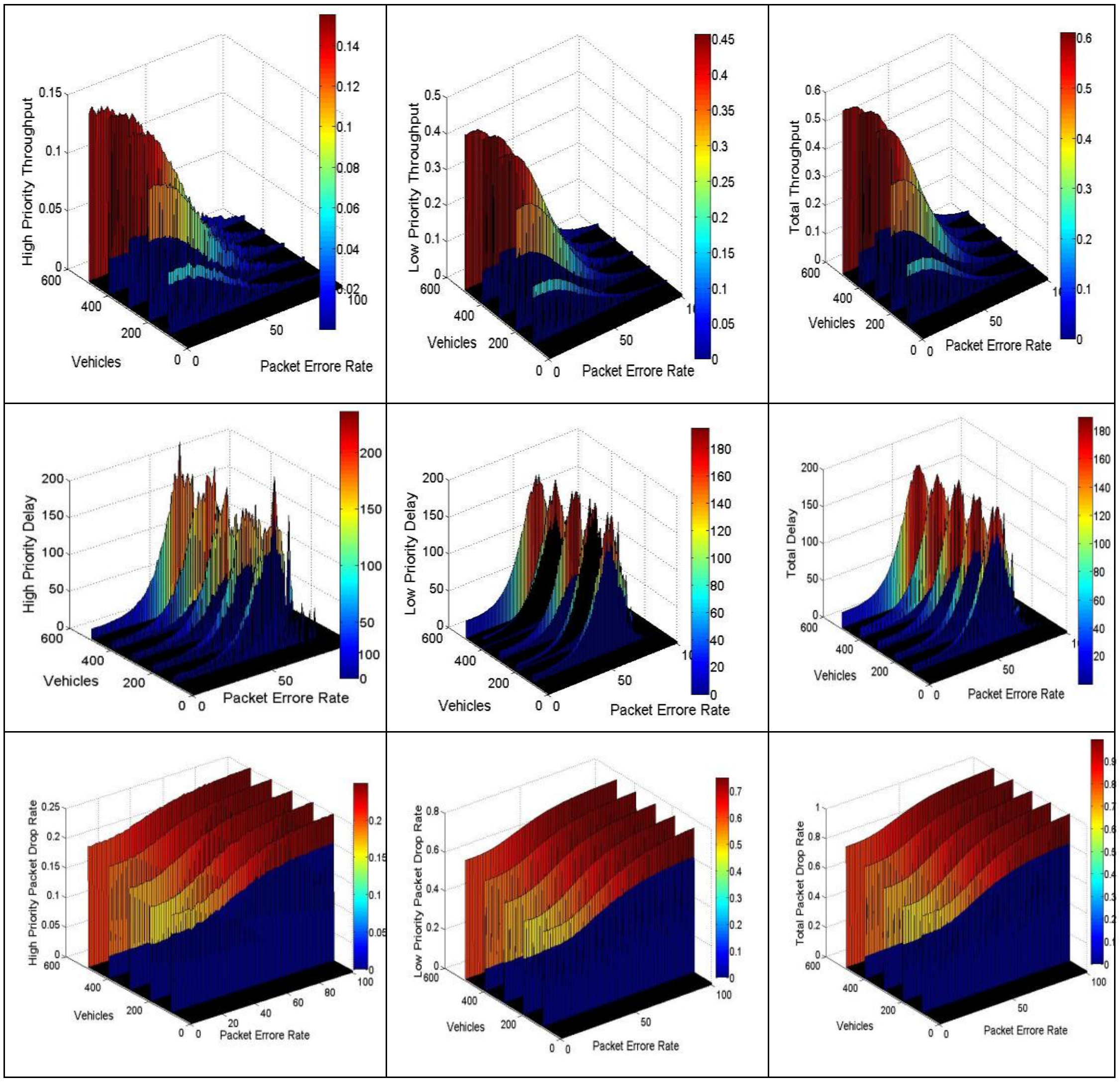


Figure 7.8: Throughput, delay and packet drop rate with variable vehicles number and packet error rate, for (road radius $R = 2$ miles and vehicle transmission range $r = 0.4$ miles) with a frame size of $N = 160$ slots.

The results show that considering mobility, the PR-ALOHA protocol still favors the high priority terminals such that in a heavy traffic scenario they still have minimum delays compared to low priority terminals. Figure 7.6 shows that as the radius of the road increases the throughput decreases, while the packet drop rate and the delay increase. Figure 7.7 shows that as the vehicle transmission range increases, the throughput increases and the delay and packet drop rate decreases. When the packet error rate increases, throughput decreases and the delay and packet drop rate increase as shown in Figure 7.8. Similarly, the simulation is performed for a different frame size (N = 80 slots, hps = 20 slots) and similar results are obtained as shown in Figures 7.9 and 7.10.

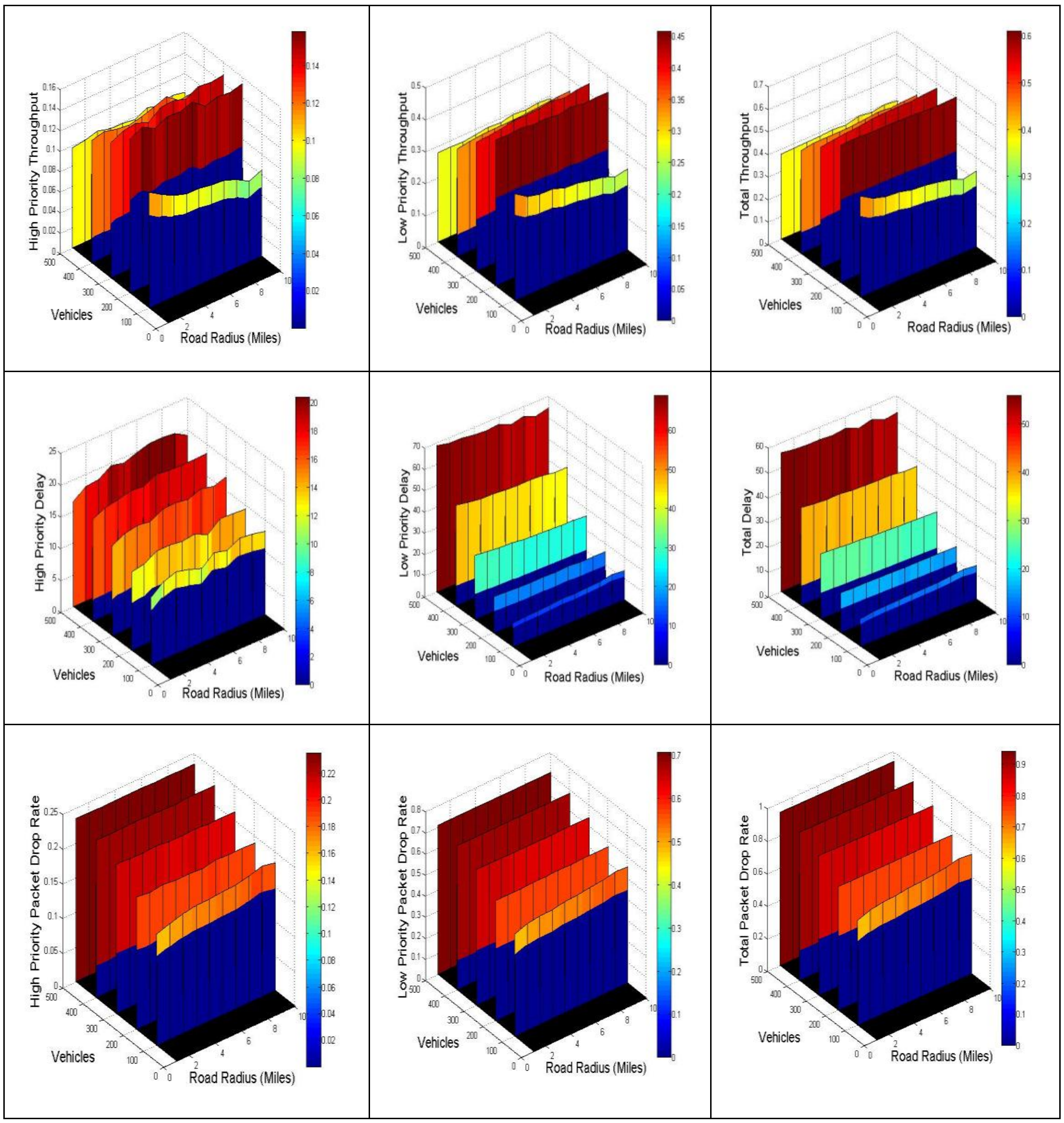


Figure 7.9: Throughput, delay and packet drop rate with variable road radius and vehicles number for (vehicle transmission range r = 0.4 miles) with a frame size of N = 80 slots.

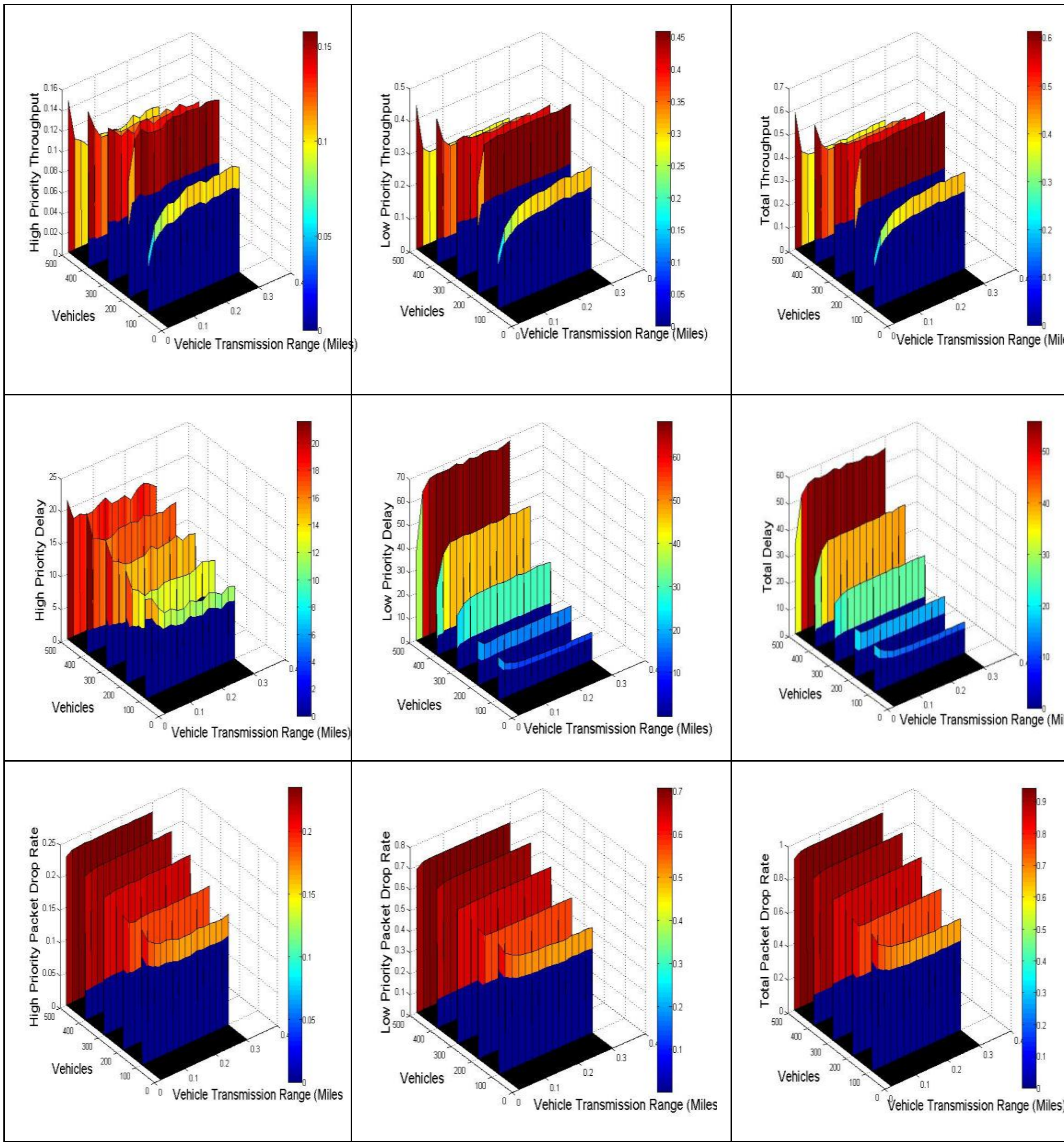


Figure 7.10: Throughput, delay and packet drop rate with variable vehicle transmission range and vehicles number, for (road radius $R = 2$ miles) and a frame size of $N = 80$ slots.

7.6 Summary

One of the important issues that affects the performance of the MAC protocol used often in IVC is vehicle mobility. In this chapter, the newly developed PR-ALOHA protocol is extended to investigate mobility using a simple but realistic and practical highway mobility model. The effect of different parameters (such as the number of vehicles on the road, road radius and transmission range) on the throughput, delay and packet drop rate is investigated. The simulation shows that in a mobile VANET environment, the PR-ALOHA protocol minimizes the delay and increases the throughput of high priority terminals while keeping the low priority terminal throughput and delay within acceptable values.

CHAPTER

8. CONCLUSIONS AND FUTURE WORK

One of the major goals of intelligent transportation systems (ITS) is to provide a set of standards for vehicular communications that will ensure safety, efficiency and convenience. The main research goal of ITS is the V2V and V2I communication where the main focus of research activities has been in the area of improving traffic efficiency and traffic safety. This work presents a new protocol that incorporates priority into the R-ALOHA protocol which may be useful in improving safety, efficiency and convenience applications in V2V communications.

The availability of priority is important for V2V communications where high priority messages such as safety related messages are generated and transmitted quickly, while regular messages of low priority can wait. The most commonly used protocols in VANETs are CSMA/CA and ALOHA based protocols. Prior research in CSMA/CA protocols, to our knowledge, considered resetting the contention window size to the minimal value after a successful transmission following the standards. In comparison of the results from our new back-off scheme approach to that from the standard implementation, throughput has improved for both ideal and non-ideal channels. In particular, the improvement in performance parameters is more noticeable for the Basic access method.

The main focus of this research is the newly developed ALOHA-based protocol with priority messaging, named Priority R-ALOHA (PR-ALOHA). The PR-ALOHA protocol is presented and both theoretical analysis and computer simulations are performed. The results of the simulations show that there is an acceptable tradeoff between throughput and delay for high priority and low priority messages. We then introduce Dynamic Slot Allocation (DSA) algorithm which is used to dynamically allocate slots for high priority traffic depending on the number of terminals. The goal of this approach includes obtaining optimal performance for throughput and delay for both high and low priority traffic in PR-ALOHA. For a low number of traffic, a smaller number of high priority slots were allocated and as the number of traffic increases, the number of high priority slots increases up to a certain value. Beyond this value, they start decreasing to give a chance for the large number of low priority traffic to transmit its data. The performance of PR-ALOHA is analyzed using Monte Carlo simulations for both the transient and steady states. The results obtained demonstrate that when high priority terminals use PR-ALOHA, they have faster access to the available channels and higher probabilities of reserving slots successfully in a shorter amount of time compared to terminals using R-ALOHA. The analytical Markov model presented is validated by simulation results. Based on the findings of this work, we conclude that PR-ALOHA has a potential in safety and efficiency applications in VANETs like IVC. This PR-ALOHA protocol may help prevent car accidents through its faster channel access, allowing warning messages to be sent to surrounding vehicles more rapidly.

Future Work:

In future work the following can be addressed:

1. Further analysis can be performed using network simulators such as ns2 where PR-ALOHA protocol can be used for communications between vehicles on the road. Furthermore, the performance of PR-ALOHA can be compared to the performance of other protocols used in V2V under the same conditions.
2. Integration of privacy and security mechanisms into the PR-ALOHA protocol to prevent unauthorized persons from gaining access to the vehicle information.
3. The mobility model can be further extended to cover more than one lane, more than one direction, and more than one segment on the road.
4. The PR-ALOHA protocol presented in this research is not restricted to VANETs. It can be used in applications where differentiated services are required.
5. The experimental evaluation of VANETs is considered expensive. Therefore, simulation techniques used in the research can be improved and more simulation models can be developed to be used in the testing procedures of evolving VANETs protocols.

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