An Adaptive Wireless Lan Mac Scheme To Achieve Maximum Throughput And Service Differentiation

Wei Zha

Follow this and additional works at: https://scholarsjunction.msstate.edu/td

Recommended Citation
https://scholarsjunction.msstate.edu/td/451

This Graduate Thesis is brought to you for free and open access by the Theses and Dissertations at Scholars Junction. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Scholars Junction. For more information, please contact scholcomm@msstate.libanswers.com.
AN ADAPTIVE WIRELESS LAN MAC SCHEME TO ACHIEVE MAXIMUM
THROUGHPUT AND SERVICE DIFFERENTIATION

By
Wei Zha

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Electrical Engineering
in the Department of Electrical and Computer Engineering

Mississippi State, Mississippi
December 2005
AN ADAPTIVE WIRELESS LAN MAC SCHEME TO ACHIEVE MAXIMUM
THROUGHPUT AND SERVICE DIFFERENTIATION

By

Wei Zha

Approved:

______________________________  ________________________________
Rose Qingyang Hu  Georgios Y. Lazarou
Assistant Professor of Electrical and  Assistant Professor of Electrical and
Computer Engineering  Computer Engineering
(Major Advisor and Director of Thesis) (Committee Member)

______________________________  ________________________________
James E. (Jim) Fowler  Nicholas H. Younan
Associate Professor of Electrical and  Professor of Electrical and Computer
Computer Engineering  Engineering
(Committee Member) (Graduate Coordinator)

______________________________
Roger King
Associate Dean of the College
of Engineering
Name: Wei Zha

Date of Degree: December 09, 2005

Institution: Mississippi State University

Major Field: Electrical Engineering

Major Professor: Rose Qingyang Hu

Title of Study: AN ADAPTIVE WIRELESS LAN MAC SCHEME TO ACHIEVE MAXIMUM THROUGHPUT AND SERVICE DIFFERENTIATION

Pages in Study: 62

Candidate for Degree of Master of Science

With the explosive deployment of wireless LAN technology in the past few years and increasing demand on multimedia applications, the efficient utilization of the precious wireless radio link resources and support of Quality of Service (QoS) in WLANs has become a prominent research issue. In this thesis, an adaptive p-persistent based IEEE 802.11 MAC scheme in WLANs has been proposed. The proposed scheme can maximize the total channel throughput, and also provide service differentiation among multiple traffic classes. This is achieved by updating the transmission probabilities for the stations that compete for transmissions in a WLAN, adaptively based on the real time network measurements. Extensive simulation experiments in ns-2 demonstrate that the proposed scheme is capable of achieving the system throughput bound and the target throughout ratios among different traffic stations in a dynamic WLAN environment. Also, the low computational complexity makes the proposed scheme a suitable choice for real-time implementation.
DEDICATION

I would like to dedicate this research to my parents.
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my major advisor, Dr. Rose Q. Hu, for her guidance and considerate support throughout my master program of study, without which this thesis would not have been accomplished. I owe her a great deal for the knowledge that I have gained in wireless networks and the precise and earnest research attitude that I have learned.

My genuine thanks go to my committee members, Dr. Georgios Y. Lazarou and Dr. James E. Fowler, for their valuable suggestions towards my research, course study, and future career.

I would also like to thank Mr. William C. Chapman, Dr. Nicholas H. Younan and Dr. James C. Harden, especially for their thoughtful concern and generous support, without which I would not have been able to complete this thesis so smoothly.

Also, I wish to thank all of my friends for their kindness and constant support, especially Feng Wu, Qinghai Gao, Weiwei Hu, Chunyu Hu, Zheng Yu, and Blake Webster.

Lastly, I want to thank my parents, Yuanming Zha and Rong Chen, for their eternal love, intensive support, and ardent encouragement.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation of Research</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Contribution</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Organization of Thesis</td>
<td>2</td>
</tr>
<tr>
<td>II. OVERVIEW AND RELATED WORK</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Overview on IEEE 802.11 MAC schemes</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1 Distributed Coordination Function (DCF)</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2 Point Coordination Function (PCF)</td>
<td>6</td>
</tr>
<tr>
<td>2.1.3 IEEE 802.11e</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Related Work</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Our Work</td>
<td>14</td>
</tr>
<tr>
<td>III. P-PERSISTENT BASED IEEE 802.11 MAC PROTOCOL</td>
<td>15</td>
</tr>
<tr>
<td>3.1 Basics of PMAC</td>
<td>15</td>
</tr>
<tr>
<td>3.1 Analytical Model of PMAC</td>
<td>17</td>
</tr>
<tr>
<td>3.1.2 Mathematical expressions for $E[N_c]$, $E[T_c]$, and $E[I]$</td>
<td>20</td>
</tr>
<tr>
<td>3.1.2.1 Average Number of Collisions $E[N_c]$</td>
<td>20</td>
</tr>
<tr>
<td>3.1.2.2 Average Collision Length $E[T_c]$</td>
<td>21</td>
</tr>
<tr>
<td>3.1.2.3 Consecutive Idle Time $E[I]$</td>
<td>22</td>
</tr>
<tr>
<td>3.1.3 Throughput Ratio</td>
<td>23</td>
</tr>
<tr>
<td>IV. ADAPTIVE PMAC SCHEME</td>
<td>26</td>
</tr>
<tr>
<td>4.1 Estimations of $E[T_c]$, $E[I]$ and $E[N_c]$</td>
<td>28</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>4.2</td>
<td>Estimation on the Number of Active Stations in Each Class ............... 29</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Equal number of stations in all traffic classes ......................... 30</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Nonequal number of stations in different traffic classes .............. 30</td>
</tr>
<tr>
<td>4.3</td>
<td>Renewal of Optimal Transmission Probabilities ................................. 32</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Equal number of stations in all traffic classes ......................... 32</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Nonequal number of stations in different traffic classes .............. 33</td>
</tr>
<tr>
<td>4.4</td>
<td>Mapping the p-persistent Transmission Probabilities into 802.11 MAC Contention Window Sizes ............................................. 34</td>
</tr>
<tr>
<td>V.</td>
<td>PERFORMANCE EVALUATION AND SIMULATION RESULTS ........... 37</td>
</tr>
<tr>
<td>5.1</td>
<td>Simulation Environments..................................................................... 37</td>
</tr>
<tr>
<td>5.2</td>
<td>Scenario 1: the number of active stations keeps unchanged.............. 39</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Case 1: equal number of stations in two classes ......................... 39</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Case 2: nonequal number of stations in two classes .............. 43</td>
</tr>
<tr>
<td>5.3</td>
<td>Scenario 2: the number of active stations changes during the simulation ........................................................................ 48</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Case 1: equal number of stations in two classes ......................... 48</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Case 2: nonequal number of stations in two classes .............. 53</td>
</tr>
<tr>
<td>5.4</td>
<td>Summary .............................................................................................. 56</td>
</tr>
<tr>
<td>VI.</td>
<td>CONCLUSION AND FUTURE WORK ........................................................ 57</td>
</tr>
<tr>
<td>6.1</td>
<td>Conclusion ........................................................................................... 57</td>
</tr>
<tr>
<td>6.2</td>
<td>Future Work ........................................................................................ 57</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>............................................................................................................ 59</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>39</td>
</tr>
</tbody>
</table>

Network Configuration (802.11b)
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Basic DCF CSMA/CA</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>DCF with RTS/CTS</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>IEEE 802.11e EDCA Implementation Model</td>
<td>8</td>
</tr>
<tr>
<td>3.1</td>
<td>Channel Access Method</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>Structure of A Virtual Transmission Time</td>
<td>18</td>
</tr>
<tr>
<td>4.1</td>
<td>The Implementation Model of the Adaptive PMAC Scheme</td>
<td>28</td>
</tr>
<tr>
<td>4.2</td>
<td>Flow Chart of the Adaptive p-persistent 802.11 MAC Scheme</td>
<td>36</td>
</tr>
<tr>
<td>5.1</td>
<td>Channel Throughput: Scenario 1 Case 1</td>
<td>41</td>
</tr>
<tr>
<td>5.2</td>
<td>Throughput Ratio: Scenario 1 Case 1</td>
<td>41</td>
</tr>
<tr>
<td>5.3</td>
<td>Station Transmission Probabilities: Scenario 1 Case 1</td>
<td>42</td>
</tr>
<tr>
<td>5.4</td>
<td>Estimation of the Number of Active Nodes: Scenario 1 Case 1</td>
<td>43</td>
</tr>
<tr>
<td>5.5</td>
<td>Comparisons between $E[I]$, $E[T_c]$: Scenario 1 Case 1</td>
<td>44</td>
</tr>
<tr>
<td>5.6</td>
<td>Channel Throughput: Scenario 1 Case 2</td>
<td>45</td>
</tr>
<tr>
<td>5.7</td>
<td>Throughput Ratio: Scenario 1 Case 2</td>
<td>46</td>
</tr>
<tr>
<td>5.8</td>
<td>Station Transmission Probabilities: Scenario 1 Case 2</td>
<td>46</td>
</tr>
<tr>
<td>5.9</td>
<td>Estimation of the Number of Active Nodes: Scenario 1 Case 2</td>
<td>47</td>
</tr>
<tr>
<td>5.10</td>
<td>Comparisons between $E[I]$, $E[T_c]$: Scenario 1 Case 2</td>
<td>48</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.11</td>
<td>Channel Throughput: Scenario 2 Case 1</td>
<td>49</td>
</tr>
<tr>
<td>5.12</td>
<td>Throughput Ratio: Scenario 2 Case 1</td>
<td>50</td>
</tr>
<tr>
<td>5.13</td>
<td>Station Transmission Probabilities: Scenario 2 Case 1</td>
<td>51</td>
</tr>
<tr>
<td>5.14</td>
<td>Estimation of the Number of Active Nodes: Scenario 2 Case 1</td>
<td>52</td>
</tr>
<tr>
<td>5.15</td>
<td>Comparisons between $E[I]$, $E[T_c]$: Scenario 2 Case 1</td>
<td>53</td>
</tr>
<tr>
<td>5.16</td>
<td>Channel Throughput: Scenario 2 Case 2</td>
<td>54</td>
</tr>
<tr>
<td>5.17</td>
<td>Throughput Ratio: Scenario 2 Case 2</td>
<td>55</td>
</tr>
<tr>
<td>5.18</td>
<td>Station Transmission Probabilities: Scenario 2 Case 2</td>
<td>55</td>
</tr>
<tr>
<td>5.19</td>
<td>Estimation of the Number of Active Nodes: Scenario 2 Case 2</td>
<td>56</td>
</tr>
<tr>
<td>5.20</td>
<td>Comparisons between $E[I]$, $E[T_c]$: Scenario 2 Case 2</td>
<td>57</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

1.1 Motivation of Research

IEEE 802.11 [1] has emerged as one of the most important and successful MAC protocols for wireless infrastructure and ad hoc LANs throughout the world. It provides a cheap and flexible wireless access capability, and it’s very facile to deploy an 802.11 WLAN in public like campuses, hospitals, and airports. With the explosive deployment of wireless LAN technology and increasing demand on multimedia applications such as real-time audio and video applications etc., ways to efficiently utilize the wireless radio links resources and support the Quality of Service (QoS) to real-time applications in WLAN has attracted a tremendous amount of research interests in the past few years. Since the original 802.11 media access control (MAC) sub-layer were designed only to support the best-effort traffic (not guaranteeing any service level to users/applications), therefore, QoS has become a prominent research issue.

1.2 Contribution

In this thesis, we propose an adaptive p-persistent based IEEE 802.11 MAC algorithm to approach the maximum throughput and achieve the service differentiation at the same time. Based on the existing p-persistent MAC analytical model proposed by the
previous researchers [2], [3], [4], [5], and [6], we extend it to better suit our proposed algorithm which is evaluated through comprehensive simulations. The major contribution of our proposed algorithm is listed as follows:

1. It can approach the maximum throughput and maintain the target throughput ratio;
2. It can handle with the network dynamics very well;
3. It has low computational complexity, which makes it an idea choice for real-time applications.

1.3 Organization of Thesis

The reminder of the thesis is organized as follows: Chapter II provides the preliminaries of the research work. In Chapter III, the details of the established analytical models for the $p$-persistent IEEE 802.11 MAC schemes are presented. Based on the theoretical models in Chapter III, the new adaptive $p$-persistent 802.11 MAC scheme is proposed in Chapter IV. Chapter V describes the details of the various simulation scenarios and also presents the performance evaluation results and analysis from the simulations. Chapter VI summarizes the discussion, gives conclusions and the future work.
CHAPTER II
OVERVIEW AND RELATED WORK

2.1 Overview on IEEE 802.11 MAC schemes

Based on the network architecture, wireless networks can be divided into two classes, namely, distributed and centralized [7]. While the Medium access control algorithms in WLANs can be classified into two broad categories: contention based MAC which is generally used in a distributed network and the reservation-based MAC that is mainly employed by an access point (AP) in centralized network architecture.

The original 802.11 MAC sub-layer is designed with two modes of communications for wireless stations: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). Both MAC schemes are designed only to support the best-effort traffic, which means no QoS mechanism has been considered.

2.1.1 Distributed Coordination Function (DCF)

DCF is a class of coordination function where the same coordination function logic is active in every station in the basic service set (BSS) whenever the network is in operation [8]. Asynchronous transmission is provided by DCF whose implementation is mandatory in all 802.11 stations (STAs). This distributed medium access scheme is based
on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol and works as follows. An STA can carry out the virtual carrier sensing at PHY MAC layer to inform all other STAs in the same Basic Service Set (BSS) of the period that the channel will be reserved for its frame transmission. The sender can set a duration field in the MAC header of data frames, or in the RequestToSend (RTS) and ClearToSend (CTS) control frames. Each STA maintains a Contention Window (CW) and a back-off timer that work as depicted in the following illustration.

As shown in Figure 2.1, if a packet arrives at an empty queue and the medium has been found idle for an interval of time longer than or equal to the time interval of Distributed InterFrame Space (DIFS), the source STA can transmit the frame at the beginning of the immediately following slot; meanwhile, other STAs defer their transmission while adjusting their Network Allocation Vectors (NAVs), and then the
backoff process begins. In case the medium is busy when the packet arrives, the station would wait until the medium has become idle for a DIFS and then sets its backoff timer. The backoff timer represents the additional time required before the next transmission attempt. In this process, an integer is randomly selected from a uniform distribution on the interval [0, CW], and the backoff timer is set to the product of this integer number. A time slot depends on the PHY layer type. The backoff timer is decremented by one time slot for every consecutive idle slot once the medium has been idle for a DIFS, and is frozen whenever the medium becomes busy. The backoff timer then resumes decreasing when the medium is detected to be idle for another DIFS period. As soon as the backoff timer expires, the STA is authorized to transmit its frame at once.

The collision detection in a wireless environment is impossible due to the significant difference between transmitted and received power levels [9]. Therefore, the destination STA sends back a positive acknowledgement (ACK) frame after a Short InterFrame Space (SIFS) upon successful receival. If the ACK is not received, the sender assumes that the transmitted frame collided, and then it increases the contention window size to (CW+1)*2-1, where $CW_{min} < CW < CW_{max}$. Also, its backoff timer is reset to a newly selected random value within [0, CW] after an EIFS interval. Besides, an optional RTS/CTS scheme can be employed before the data transmission in order to reduce the overhead caused by the frame collision and the hidden terminal effect. As depicted in Figure 2.2, both the physical carrier sensing and the NAV timer setting will act together to determine whether the channel is idle or busy. That is, the source sends out a short RTS before each transmission; and the receiver replies with a CTS if it is ready to receive.
Once the source receives the CTS, it begins data transmission. All of the other stations hearing a RTS/CTS or a data frame in the BSSS update their NAVs and will not start transmissions before the updated NAV timers reach zero [9].

![DCF with RTS/CTS](image)

**Figure 2.2 DCF with RTS/CTS**

### 2.1.2 Point Coordination Function (PCF)

Unlike DCF, contention-free PCF is an optional polling-based access method, which requires the Access Point (AP) as a Point Coordinator (PC). If a BSS is set up with PCF-enabled, the channel access time is divided into periodic intervals named beacon intervals. A beacon interval is composed of a Contention-Free Period (CFP) and a Contention Period (CP). The time used by the PC to generate beacon frames is called Target Beacon Transmission Time (TBTT). During a CFP, the AP maintains a list of registered STAs and grants an STA the permission to transmit data frame using a polling
mechanism. A CFP begins when the AP obtains access to the wireless medium. In order to ensure that no DCF STAs will interrupt the operation of the PCF, an AP waits for a PCF InterFrame Space (PIFS), which is shorter than DIFS and longer than SIFS, to start the PCF. During a CP, the DCF scheme is used, and the beacon interval must allow at least one DCF data frame to be transmitted.

2.1.3 IEEE 802.11e

Wireless links vary over time and place, due to their distinct characteristics, such as the channel fading, bursts of frame loss, large packet delay, and jitter etc. The support of QoS in WLAN becomes an urgent need to meet the ever-increasing demand on the multimedia applications in the near future. However, the IEEE 802.11 WLAN was originally designed for best-effort services, and its legacy DCF and PCF have limitations on supporting QoS. Recently, IEEE 802.11e [10] was proposed to enhance QoS for delay-sensitive applications. It is expected that this QoS enhancement for 802.11 WLAN will enable a huge market for audio and video transmissions in WLAN-based home networks, as well as applications like VoIP in WLAN hot-spot areas.

In order to provide differentiated services and support prospective multimedia applications, IEEE 802.11 Working Group E [11] has defined a new mechanism, Hybrid Coordination Function (HCF). HCF is composed of two access methods: Enhanced Distributed Channel Access (EDCA) mechanism for contention based data transmission and HCF Controlled Channel Access (HCCA) for contention free data transmission.

EDCA is an extension of the original DCF mechanism to support prioritized traffic classes. In EDCA, each priority is mapped to an Access Category (AC); each QoS-
enhanced STA has 4 ACs to provide 8 user priority levels. Each AC queue works as an independent DCF STA and maintains its own backoff parameters. Figure 2.3 depicts the implementation model of EDCA.

There are two primary methods introduced to support service differentiation. The first one chooses different InterFrame Space (IFS) sizes for different ACs. Unlike using DIFS in DCF, an Arbitration IFS (AIFS) is used in EDCA. The second method allocates different CW sizes for different ACs so that the high-priority AC can have more chances to transmit frames than the low-priority ACs. To deal with the internal contention, a scheduler inside the QoS station (QSTA) will grant a Transmission Opportunity (TXOP),

Figure 2.3 IEEE 802.11e EDCA Implementation Model
the right to use the medium for a period of time, to the highest priority AC in case the backoff counter of two or more parallel ACs in one QSTA reach zero simultaneously. Once a QSTA has gained a TXOP, it can send more than one frame without contending for the medium again. However, the TXOP limit should not be longer than the time required for the transmission of the largest data frame. Meanwhile, the other colliding ACs will enter a backoff process and double the CW sizes as if there is an external collision.

The HCCA mechanism can begin the controlled channel access mechanism in both CFP and CP intervals, while PCF is only allowed in CFP. A Hybrid Coordinator (HC) maintains a nearly continuous sequence of frame exchanges with short and fixed delays in-between. Instead of using CW in EDCA, the inter-frame delay adopted by HCCA does not increase accordingly to the increasing traffic load. When the HC sends a poll to a QSTA, the QoS control field contains a TXOP limit value which specifies the duration of the granted TXOP. The HC is responsible for allocating time on the medium through the use of polled TXOPs [12]. After receiving a QoS CF-poll frame, a polled QSTA is allowed to transmit multiple MAC frames denoted by Contention-Free Burst (CFB), with the total access time not exceeding the TXOPLimit. All of the other QSTAs set their Network Allocation Vector (NAVs) with the TXOPLimit plus a slot time.

2.2 Related Work

In recent decades, researchers have done an extensive amount of work on the performance evaluation and QoS provision of contention-based IEEE 802.11 MAC protocol. We sort those work into two main categories: one is the upcoming IEEE
802.11e with different featured access schemes to support QoS; and the other one is p-persistent version of 802.11 MAC protocol that improves the performance by adjusting the backoff time and fine-tuning the transmission probabilities. In addition, there are some work emphasize on scheduling [13], saturation throughput [14], and delay assurance [15].

S. Mangold, et al. have done a comprehensive overview of the new features of an upcoming new standard IEEE 802.11e to support QoS in WLANs in [8], [16], [17], [18]. They evaluate the QoS support with two new mechanisms, EDCF and HCF respectively. The performance analysis shows that the upcoming 802.11e standard would be an efficient mechanism to support a wide variety of applications in WLANs.

Focused on this hot spot, Q. Ni et al propose an adaptive Fair EDCA in [19] as an extension of EDCF, and also an efficient scheduling scheme, FHCF in [20] to improve the quality of multimedia applications and provide good fairness. The adaptive fair EDCA increases the CW value during deferring period when the channel is sensed busy, and uses an adaptive fast backoff mechanism while the channel is idle. The proposed FHCF scheme includes two schedulers: the QoS-enhanced AP (QAP) scheduler and the node scheduler. The QAP scheduler uses a window of previous estimation errors for each traffic stream in each QSTA to adapt the computation of the TXOP allocated to that QSTA [21]. The node scheduler can redistribute the unused time among different traffic streams in a QSTA.

Both the proposed EDCF and HCF MAC coordination functions are very sensitive to protocol parameters as investigated in [22]. The simulation comparisons
performed by the authors in [22] between EDCF and HCF indicates that HCF provides more efficient channel utilization and less channel contention.

While the above research works have focused on several enhanced versions of basic 802.11 DCF functions, such as EDCF and HCF, for the upcoming IEEE 802.11e protocol, some other researchers addressed the WLAN QoS provisioning issue based on the $p$-persistent version of IEEE 802.11 MAC protocol. Among all of these works are F. Cali [2], [3], [4], Bianchi [23], L. Bononi [24] and Y. Ge [5], [6].

F. Cali, M. Conti, and E. Gregori focus on the capacity analysis of the IEEE 802.11 standard for wireless LANs and derived an effective formula for the protocol-capacity calculation [4]. The performance of 802.11 protocols is evaluated with a dynamically tuned backoff window size in [2], [25]. The analytical model with the detailed mathematical derivation is presented in [3]. The paper shows that the performance of $p$-persistent IEEE 802.11 protocol closely approximates the legacy 802.11 DCF protocol if the two have the same average backoff window size.

In [23], an Adaptive Contention Window mechanism, which dynamically selects the optimal transmission probability $p$ according to the estimate of the number of contending stations, was proposed. Bianchi, et al. proved that the system throughput depends on the transmission probability $p$ and the number of active stations, $N$. The author proposed an algorithm to dynamically adapt $p$, so that the channel throughput can be maximized. However, only one single traffic class was considered in this study, so the scheme is not capable of differentiating QoS among different traffic classes.
Being aware of an appropriate tuning of the congestion control mechanism could drive the IEEE 802.11 protocol close to its optimal behavior, L. Bononi, et al. [24] propose an Asymptotically Optimal Backoff (AOB) to dynamically adapt the backoff window size to the current network contention level and guarantee that the wireless LAN asymptotically approaches its optimal channel utilization. The AOB mechanism doesn’t require estimation of the number of active stations. Instead, it monitors the network contention level through the estimation of the slot utilization (S_U) and the average size of transmitted frames. The estimated S_U is used as a feedback signal to control the stations’ behavior via the computation of the transmission probability (P_T).

In [5], Y. Ge and J. Hou extend the previous work in [2], [3], [4] to support QoS differentiation in wireless LANs. Their algorithm can achieve service differentiation among multiple traffic classes in wireless LANs and also maximize the channel throughput at the same time. A simple but effective mechanism is also proposed by the authors to estimate the number of active stations for each traffic class in a QoS basic service set to handle the network dynamics and optimize the system parameters [6]. They also propose the conversion from the optimal transmission probability of $p$-persistent IEEE 802.11 to the contention window size in the contention window based IEEE 802.11 protocol. The performance study shows that the algorithm can effectively achieve service differentiation among various services and is able to achieve the maximum channel throughput. The algorithm, however, has a high computational complexity and is not suitable for the real-time adaptation.
Besides p-persistent based 802.11 protocols, some other researchers [26], [27] come up with different algorithms that dynamically adjust the contention window size to achieve high throughput performance.

The basic idea of the Fast Collision Resolution (FCR) algorithm in [26] is to accelerate the collision resolution and reduce the average idle time. The FCR adopts smaller initial (minimum) contention window size but larger maximum CW size than the legacy IEEE 802.11 MAC. Meanwhile, it increases the CW size of a station when it is in collision or deferring state and reduces the backoff timers exponentially when a fixed number of consecutive idle slots are detected [26]. Instead of estimating the number of active nodes, consecutive idle time, etc, the FCR algorithm just performs some modification to the original 802.11 DCF protocol. In this paper, the study only shows the performance evaluation of the FCR algorithm. There is no comparison with the previous work.

The authors propose a fully distributed MAC adaptation method in [27] in order to support QoS differentiations. In their scheme, the network monitors the network statistics periodically, and the collision probability is calculated accordingly to update the MAC parameter (Contention Window) for the stations. It updates the CW to achieve the tradeoff between the idle period wasted on backoff and the collision period due to the transmission collisions. Their method can differentiate services efficiently and improve the system performance by reducing the delay.
2.3 Our Work

Following the current research trend towards $p$-persistent IEEE 802.11e protocol, we notice that the work in [2] and [3] successfully adapts the transmission probability for each station to gain the maximum throughput, but only one traffic class is considered in their work. Thus their scheme is not able to support QoS. The simulation results in [6] show that the proposed scheme can achieve satisfactory system throughput and desired throughput ratios among different traffic classes. The scheme, however, is not able to adaptively tune the station transmission probabilities once there is a change in the network configuration. In this thesis, we propose a $p$-persistent based IEEE 802.11 MAC (PMAC) protocol for WLAN to maximize the total wireless channel throughput and also achieve the target throughput ratios among different traffic classes in a dynamic WLAN environment, where stations join and leave the network randomly. This is achieved by periodically updating the transmission probability $p$ for each station based on the real-time network performance measurements. Extensive simulative experiments are carried out in ns-2 [28] (version 2.26) to test the accuracy and efficiency of the proposed adaptive PMAC scheme. The simulations reveal a great consistency between the simulation results and the theoretical analysis.
CHAPTER III
P-PERSISTENT BASED IEEE 802.11 MAC PROTOCOL

In this chapter, we present the existing work for p-persistent based IEEE 802.11 MAC (PMAC) protocol, shown in the research carried out in this thesis. As it is mentioned in [4] and [6], the memory-less property of the geometric distributed backoff algorithm for the p-persistent IEEE 802.11 MAC protocol makes it better suited for the analytical studies. The mathematical model presented in this chapter provides a solid foundation for the adaptive PMAC scheme proposed in Chapter III.

3.1 Basics of PMAC

The $p$-persistent based IEEE 802.11 MAC protocol differs from the standard protocol only in the selection of backoff timer. The PMAC scheme determines the backoff time of each station by sampling from a geometric distribution with parameter $p$, instead of using the binary exponential backoff like in DCF. In a PMAC scheme, a station transmits with a probability $p$ at the beginning of each empty slot, while the transmission defers with a probability $1-p$. The study in F. Cali, et al. [4] shows that a $p$-persistent IEEE 802.11 protocol closely approximates the window based 802.11 DCF protocol if the two operate with the same average backoff window size.

In the IEEE 802.11 DCF standard, a slotted binary exponential backoff technique is used to arbitrate the access. A random backoff interval is uniformly chosen in
$[0, CW - 1]$ to initialize the backoff timer, where $CW$ denotes the contention window. This backoff timer is decreased as long as the channel is sensed idle, paused while a frame transmission is in progress, and the residual backoff time is then calculated in succession. When the channel becomes idle again for a more than DIFS period, the backoff timer is resumed or reactivated with the previous computed leftover backoff time. As shown in Figure 3.1, the time followed slotted and each slot equals the time required for a STA to detect the frame transmission from any other STA. A station attempts to transmit at the next time slot after the expiration of the backoff timer.

![Figure 3.1 Channel Access Method](image)

For the geometric-distributed backoff algorithm of PMAC, due to its memory-less property, whenever the backoff timer is started, resumed, or reactivated, the backoff interval will be reselected from a geometric distribution with parameter $p$. That is, no more residual backoff time will be called back to execute during the entire backoff procedure.

Previous works have shown that the fine-tuning of the IEEE 802.11 backoff algorithm can significantly improve capacity or channel utilization and service quality of WLANs [3], [23], [29], and [30]. If an STA has an accurate knowledge of the network
configuration and traffic status, it is possible to set its backoff algorithm to approach the theoretical bound of the protocol capacity.

3.1 Analytical Model of PMAC

The existing PMAC analytical models [2], [3], and [5] are usually based on the following assumptions:

1. Asymptotic condition: all of the stations always have packets ready for transmission. We assume that each traffic class has a finite number of STAs operating in the asymptotic conditions.

2. Presume that the hidden-terminal phenomenon never occurs (i.e., all the stations can always hear other stations). Therefore, we do not need to consider the RTS/CTS optional mechanism.

3. The backoff interval is sampled from a geometric distribution with parameter $p$.

4. There are $P$ traffic classes in total, while each class consists of $N_i$ stations ($1 \leq i \leq P$).

5. A class-$i$ station transmits its frame with the probability $p_i$ in the $p$-persistent based IEEE 802.11 ($1 \leq i \leq P$).

6. The size $m_i$ of a packet sent by a class-$i$ station is uniformly distributed between $(x_0, x_1)$ [5]:

$$P(m_i \leq x) = \begin{cases} 
0 & x < x_0, \\
\frac{x - x_0}{x_1 - x_0} & x_0 \leq x \leq x_1, \\
1 & x > x_1.
\end{cases} \quad (3.1)$$
The wireless channel throughput is an important metric to evaluate the system performance. It can be estimated at the end of each successful transmission. Assume the packet length is *i.i.d* sampled from a geometric distribution with parameter $q$. As shown in Figure 3.2, the time interval between two successful transmissions is referred to as virtual transmission time [4], or the renewal period, which includes one successful transmission and several collision intervals.

![Figure 3.2 Structure of A Virtual Transmission Time](image)

In [4], by using the regenerative property, the channel throughput ratio is defined as:

$$\rho_{\text{max}} = \frac{E[m]}{E[T_v]} \quad (3.2)$$

$E[T_v]$ is the average virtual transmission time, and $m$ is the average message length. Based on F. Cali’s verification in [2], [3] and Y. Ge’s derivation in [5], $E[T_v]$ can be represented as:

$$E(T_v) = E\left[\sum_{i=1}^{N_{\text{col}}}(\text{Idle}_i p_i + \text{Coll}_i + \tau + \text{DIFS})\right] + E[\text{Idle}_N p_{N_{\text{col}}+1}] + E[S] \quad (3.3)$$

$$= E[N_{\text{col}}] \cdot (E[T_c] + \tau + \text{DIFS}) + (E[N_{\text{col}}] + 1) \cdot E[I] + E[S];$$

Where,
$E[S]$ : time required to complete a successful transmission (including the protocol overheads);

$E[N_c]$ : average number of collisions in a virtual transmission time;

$E[I]$ : average consecutive idle time;

$T_c$: Collision time; if there is a collision, it equals to the maximum length (in the unit of time slot) of packet transmitted during collision; if no collision happens, it is 0;

$E[T_c]|_{Collision}$ : average collision time given that a collision occurs;

$\tau$ : propagation delay for a data frame transmitting from a source to a destination node.

$ACK$ : the length of the acknowledgement frame;

By taking into account the protocol behavior, $E[S]$ can be expressed as:

$$E[S] \approx E[m] + 2\tau + SIFS + ACK + DIFS$$

(3.4)

Considering the equations (3.3) and (3.4), we can see that with a given $E[m]$, the maximum channel throughput, $throughput_{max}$ (or $\rho_{max}$) corresponds to the minimum virtual transmission time $\min(E[T_v])$. Thus, the transmission probabilities for the STAs that lead to $\min(E[T_v])$ will result in the maximum channel throughput. Given a WLAN, the average virtual transmission time $E[T_v]$ can be estimated by measuring channel idle period, number of collisions, and number of successful transmissions. In order to minimize $E[T_v]$ that lead to the achievable maximum system capacity, [2] and [5] establish the mathematical relationships between the variables in equation (3.3) and the
station transmission probabilities so that the transmission probabilities that achieve the optimal network performance can be derived.

3.1.2 Mathematical expressions for \( E[N_c] \), \( E[T_c] \), and \( E[I] \)

3.1.2.1 Average Number of Collisions \( E[N_c] \)

Let \( N_{ts} \) denote the number of transmitting stations in the slot immediately after an idle DIFS interval.

\[
P_{\text{collision}} = P(N_{ts} \geq 2 \mid N_{ts} \geq 1) = \frac{1 - P(N_{ts} = 0) - P(N_{ts} = 1)}{1 - P(N_{ts} = 0)} \quad (3.5)
\]

\[
P_{\text{success}} = P(N_{ts} = 1 \mid N_{ts} \geq 1) = \frac{P(N_{ts} = 1)}{P(N_{ts} \geq 1)} \quad (3.6)
\]

Based on the probability that a collision occurs, \( P_{\text{collision}} \), and the probability that a transmission will be successful, \( P_{\text{success}} \), the distribution of the number of collisions, \( (N_c) \), in a virtual transmission time is shown as:

\[
P(N_c = j) = P_{\text{collision}}^j \cdot P_{\text{success}} \quad (3.7)
\]

Therefore, the average number of collisions, \( E[N_c] \), is expressed as:
\[ E[N_c] = \sum_{i=0}^{\infty} i \cdot P(N_c = i) \]
\[ = \frac{1 - \prod_{i=1}^{\infty} (1 - p_i)^{N_c}}{\sum_{i=1}^{\infty} N_c \cdot p_i \cdot (1 - p_i)^{N_c} \prod_{i=1}^{\infty} (1 - p_i)^{N_c} - 1} \] 

3.1.2.2 Average Collision Length \( E[T_c] \)

Due to the lack of the implementation of a collision detection mechanism in IEEE 802.11 protocol, a collision will last until all of the colliding packets have completed their transmissions once it happens; even though all of them are dumped finally. The actual length of a collision (in the unit of time slot) is hence equal to the maximum length of all the packets involved:

\[ T_c = \max(L_1, L_2, \ldots, L_{N_c}) \] (3.9)

Where, \( L_j \) is the length of the packet sent of the \( j \)-th station involved in the collision \( (2 \leq j \leq N_{cp}) \). Then, we get:

\[ E[T_c] = \sum_{j=0}^{N_{cp}} \sum_{j_2=0}^{N_{cp}} \cdots \sum_{j_p=0}^{N_{cp}} [E(T_c | N_{cp1} = j_1, N_{cp2} = j_2, \ldots, N_{cp_p} = j_p) \cdot P(N_{cp1} = j_1, \ldots, N_{cp_p} = j_p | N_{cp} > 1)] \] (3.10)

With the assumption 6, the conditional expectation term in equation (3.10) can be rewritten as:
\[ E(T_c \mid N_{cp} = j_1, N_{cp} = j_2, \ldots, N_{cp} = j_p) = \int_{x_0}^{x_1} xd(P(T_c \leq x)) = \int_{x_0}^{x_1} xd\left(\frac{x-x_0}{x_1-x_0}\sum_{i=1}^{p}x_i\right)\]  
\[ = x\left(\frac{x-x_0}{x_1-x_0}\sum_{i=1}^{p}x_i\right)\left|_0^{x_1} - \int_{x_0}^{x_1} \frac{x-x_0}{x_1-x_0}\sum_{i=1}^{p}x_i\right| dx \]
\[ = \frac{x_0}{\sum_{i=1}^{p}j_i + 1} \]

And the conditional probability term can be expressed as:

\[ P(N_{cp} = j_1, N_{cp} = j_2, \ldots, N_{cp} = j_p \mid N_{cp} > 1) \]
\[ = \prod_{i=1}^{p} \left( \begin{array}{c} N_i \\ j_i \end{array} \right) p^{j_i} (1 - p)^{N_i - j_i} \]
\[ = \frac{\prod_{i=1}^{p} \left( \begin{array}{c} N_i \\ j_i \end{array} \right) p^{j_i} (1 - p)^{N_i - j_i}}{1 - P(N_{ts} = 0) - P(N_{ts} = 1)} \]
\[ = \frac{\prod_{i=1}^{p} \left( \begin{array}{c} N_i \\ j_i \end{array} \right) p^{j_i} (1 - p)^{N_i - j_i}}{1 - \prod_{i=1}^{p} (1 - p)^{N_i} - \sum_{i=1}^{p} N_i p_i (1 - p_i)^{N_i - 1} \prod_{j \neq i} (1 - p_j)^{N_j}} \]

Combining equations (3.11) and (3.12), the average collision length \( E[T_c] \) can be derived. Considering the relation between \( E[N_c] \) and \( E[T_c] \), we have:

\[ E[T_c] = E[T_c]_{\text{collision}} \cdot \frac{E[N_{col}]}{E[N_{col}]+1} \]  
(3.13)

3.1.2.3 Consecutive Idle Time \( E[I] \)

If there is only one traffic-class, each STA in the network transmits with the same probability \( p \).

\[ P(N_{ts} \geq 1) = 1 - (1 - p)^N \]  
(3.14)
\[ E[I] = (1 - (1 - p)^N) \cdot \sum_{i=1}^{\infty} i((1 - p)^N)^i \cdot t_{slot} \]
\[ = \frac{(1 - p)^N}{1 - (1 - p)^N} \cdot t_{slot} \]  

(3.15)

For multiple-class (P) networks, the STAs within the same traffic class have the same probability \( p_i (i = 1, 2, \ldots P) \):

\[ P_i(N_{ts} \geq 1) = 1 - (1 - p)^N_i \]  

(3.16)

the expression of \( E[I] \) for multiple classes can be represented as

\[ E[I] = \sum_{i=1}^{\infty} i \cdot (P(N_{ts} > 0) \cdot (P(N_{ts} = 0))^i \cdot t_{slot} \]
\[ = \frac{\prod_{i=1}^{P} (1 - p_i)^{N_i}}{1 - \prod_{i=1}^{P} (1 - p_i)^{N_i}} \cdot t_{slot} \]  

(3.17)

With \( E[I] \), \( E[T_c] \), and \( E[N_c] \) expressed as functions of the active number of STAs in each class, \( N_i \) and the transmission probability set, \( p_i \), equations (3.3) and (3.4) indicate that \( E[T_u] \) can also be expressed as a function of these variables.

### 3.1.3 Throughput Ratio

For the sake of provisioning the QoS for prioritized classes, the throughput ratio is accordingly introduced in [5] and [6]. There are two types of throughput ratios. One is defined as the throughput ratio between two different classes; the other one is defined as the ration between two stations belonging to different classes.

In [5], the probability that a packet from class-i successfully transmits in a virtual transmission time is expressed as:
\[ P_{\text{pkt}}(i) = \frac{N_i p_i (1 - p_i)^{N_i - 1} \prod_{j \neq i}^p (1 - p_j)^{N_j}}{\sum_{i=1}^p N_i p_i (1 - p_i)^{N_i - 1} \prod_{j \neq i}^p (1 - p_j)^{N_j}} \] (3.18)

Recalling the equation (3.2), the throughput for all class-\(i\) stations hereby can be expressed as:

\[ \rho_i = \frac{E[m_i] P_{\text{pkt}}(i)}{E[T_v]} \] (3.19)

Thus, the throughput ratio between class-\(i\) and class-\(j\) (\(i \neq j\)) is expressed as [5].

\[ r_{ij} = \frac{\rho_i}{\rho_j} = \frac{E[m_i] P_{\text{pkt}}(i)}{E[m_j] P_{\text{pkt}}(j)} = \frac{E[m_i]}{E[m_j]} \cdot \frac{N_i \cdot p_i \cdot (1 - p_j)}{N_j \cdot p_j \cdot (1 - p_i)} \] (3.20)

The throughput ratio between a class-\(i\) station and a class-\(j\) station (\(i \neq j\)) is defined as [5].

\[ \hat{r}_{ij} = \frac{\rho_i/N_i}{\rho_j/N_j} = \frac{N_j}{N_i} \cdot r_{ij} \] (3.21)

In a WLAN that is capable of support QoS provisioning, the throughput ratios are usually pre-defined as network parameters. Based on the mathematical models presented above, the optimal transmission probability set that satisfies the throughput ratio constraints defined by equation (3.20) and minimizes \(E[T_v]\) can be calculated. The simulation results in [5] show that satisfactory channel throughput and throughput ratios can be achieved. However, expressing \(E[T_v]\) in terms of transmitting probabilities and minimizing \(E[T_v]\) with respect to the transmission probabilities are not trivial tasks. This method involves high computational complexity, which prohibits it from a real-time adaptive implementation. The algorithm based on the similar mathematical models in [2]
and [3] can dynamically adapt the transmission probability for each station to achieve the maximum throughput based on the network measurements. But the scheme assumes that each station in the network transmits with the same probability so that it does not provide any QoS differentiation among different stations.

In chapter III, we propose an adaptive $p$-persistent MAC protocol to achieve both the maximum channel throughput and QoS differentiations in WLANs by fine tuning the transmission probabilities for different stations in the network based upon network measurements and simplified mathematical models between these measurements. Be aware that the minimal $E[T_{\nu}]$ is equivalent to the maximum throughput, and the stable throughput ratio implies a good service differentiation. The basic idea of the adaptive scheme is to adapt the transmission probability for the stations in each class to minimize $E[T_{\nu}]$ while keeping the throughput ratios at target values.
CHAPTER IV
ADAPTIVE PMAC SCHEME

In a high capacity WLAN, the mobile stations join and leave the network randomly. In order to achieve the maximum throughput and QoS differentiation in a dynamic WLAN environment, the transmission probability of each class should be dynamically adapted correspondingly. Based on the established modelling analytical model and the real-time measurements, the number of active nodes for each traffic class and the transmission probability for a station can be accordingly updated. Therefore, the system throughput bound can be achieved and the preset throughput ratios can be maintained. The required real-time measurements include the consecutive idle time $E[I]$, the average number of collisions $E[N_c]$ in a virtual transmission time $E[T_v]$, and the average collision time $E[T_c]$.

According to [3], [5], and [6], the maximal throughput is achieved when the station transmission probabilities minimize $E[T_c]$ (see equation (3.3)). It is difficult and computationally expensive to derive a close form mathematical expression for the optimal transmission probabilities based on this condition. As seen in [2], [3], and [28], the channel capacity is very close to its theoretical maximum bound when the average time spent on idle stage equals the average time spent on collisions, i.e.,

$$E[T_c] \approx E[I]$$  \hspace{1cm} (4.1)
Substitute $E[T_c]$ with $E[T_c]|_{\text{collision}}$. According to the equation (3.13), the above equation can be rewritten as

$$E[T_c]|_{\text{collision}} \cdot E[N_c] \approx (E[N_c] + 1) \cdot E[I]$$

(4.2)

Using condition (4.1) as the optimal throughput constraint, the complexity of the calculation and adaptation of the optimal transmission-probability set has been greatly reduced. F. Cali et al [2] used this constraint to derive the near-optimal transmission probability for a single-class case. We extend this method to approximate the optimal condition for a multiple-class network. If the network measurements on $E[T_c]$ and $E[I]$ show that the current network works away from the optimal point, the transmission probability ($p_i$) for each station class will be adapted based on the algorithm introduced later in this chapter. Besides the measurements on $E[T_c]$ and $E[I]$, knowledge of the number of active stations is also needed for each class. The number of nodes for each class can be calculated based upon the measurements of $E[N_c]$ and $E[I]$ when the number of traffic classes is less than 2. While for a more general case (i.e., the number of traffic classes is more than two), the number of active nodes for each class can be counted through the statistics on the channel access history due to the lack of network information for the station number estimation. To facilitate the analysis, we assume that the number of traffic classes is equal to 2 for the following sections. The algorithm applies to any number of traffic classes.

As Figure 4.1 indicates, the instantaneous idle time ($I_n$) and the collision time ($T_c$) for each collision are measured after each transmission attempt; and the number of
collisions \((N_c)\) during a virtual transmission time is measured after each successful transmission. \(E[T_c]\), \(E[N_c]\) and \(E[I]\) are updated periodically based on the renewed measurements. The \(p_i\) for each traffic class will be adapted to its new optimal value if the values of \(E[T_c]\), \(E[I]\), and the number of stations \((N_i)\) have significant changes.

![Figure 4.1 The Implementation Model of the Adaptive PMAC Scheme](image)

4.1 **Estimations of** \(E[T_c]\), \(E[I]\) and \(E[N_c]\)**

A transmission attempt can lead either to a success or a collision. When a collision occurs, the maximum packet length in time slot among all of the involved packets is recorded as \(T_c\). If the transmission attempt succeeds, \(T_c\) is set at zero. Accordingly, the moving average collision time is updated after each transmission attempt, failure, or success:
\[ E[T_{c}]_{n+1} = \alpha \cdot E[T_{c}]_{n} + (1 - \alpha) \cdot T_{c(n+1)} \] (4.3)

The \( \alpha \) is used as a smoothing factor in the network protocols to avoid fluctuations.

In the event of a collision, all of the involved packets are discarded. The stations begin to sense the channel again. After a DIFS-long idle period, the backoff timer is activated for the next transmission attempt. The elapsed backoff interval between two consecutive transmission attempts is marked as \( I_{n} \). Accordingly, the average consecutive idle time \( E[I] \) is estimated by:

\[ E[I]_{n+1} = \alpha \cdot E[I]_{n} + (1 - \alpha) \cdot I_{(n+1)} \] (4.4)

After a successful transmission, the number of collisions happening within a virtual transmission time period is recorded as \( N_{c} \), which is used to estimate \( E[N_{c}] \):

\[ E[N_{c}]_{n+1} = \alpha \cdot E[N_{c}]_{n} + (1 - \alpha) \cdot N_{c(n+1)} \] (4.5)

\( N_{c} \) is reset to null after a virtual transmission completes, ready for the next round computation.

4.2 Estimation on the Number of Active Stations in Each Class

An STA can estimate its active number of nodes if there is enough network information available. We derive the expression of estimating \( N_{i(n)} \) for two cases separately: all of the traffic classes have the same number of active stations, and different traffic classes have different number of active stations.
4.2.1 Equal number of stations in all traffic classes

Assuming that all of the traffic classes have exactly the same number of active STAs, it is evident that $N_i(n) = N_j(n), (0 < i, j < P, and \; i \neq j)$. The estimation on the station number in this case is rather simple. Rewrite equation (3.17) as

$$N_{\text{temp}0(n)} = N_{\text{temp1}(n)} = \cdots = N_{\text{temp}P(n)} = \frac{\ln\left(\frac{E[I]_{n+1}}{E[I]_{n+1} + t_{slot}}\right)}{\ln[(1 - p_{0}(n))(1 - p_{1}(n)) \cdots (1 - p_{P(n)})]} \quad (4.6)$$

This formula provides an accurate estimation on $N_i$ in the stationary network status, while $E[I]$ and $p_{i}(n) (0 \leq i \leq P)$ are constant. However, taking into account of the statistic fluctuations and network configuration changes, we use a smoothing factor $\alpha$, so that the moving average estimation is used in the calculation:

$$N_{i(n+1)} = N_{i(n)} \cdot \alpha + N_{\text{temp}(n+1)} \cdot (1 - \alpha) \quad (4.7)$$

4.2.2 Nonequal number of stations in different traffic classes

In reality, various traffic classes most likely have different number of active nodes. In the equal station case, only one number needs to be estimated. In the nonequal station case, we need to estimate the number of active stations for each class, which could make the estimation much more complicated and less accurate. Based on our analysis, there are only enough measurements in the network to estimate the station numbers for two traffic class cases. If the number of traffic classes exceeds 2 and each class has a different number of active nodes, we will introduce a new method to estimate the station numbers.
Recall the expressions for \(E[I]\) and \(E[N_c]\) (equation (3.17) and (3.8)), and rewrite them for the two-class case as:

\[
E[I]_{n+1} = \frac{(1 - p_{0(n)})^{N_{0(n)}} \cdot (1 - p_{1(n)})^{N_{1(n)}}}{1 - (1 - p_{0(n)})^{N_{0(n)}} \cdot (1 - p_{1(n)})^{N_{1(n)}}}
\]  \hspace{1cm} (4.8)

and

\[
E[N_c]_{n+1} = \frac{1 - (1 - p_{0(n)})^{N_{0(n)}} (1 - p_{1(n)})^{N_{1(n)}}}{N_{0(n)} p_{0(n)} (1 - p_{0(n)})^{N_{0(n)-1}} (1 - p_{1(n)})^{N_{1(n)-1}} (1 - p_{0(n)})^{N_{0(n)}} - 1}
\]  \hspace{1cm} (4.9)

Rearranging equations (4.8) and (4.9), \(N_{i(n)}\) can be expressed as follows:

\[
\begin{align*}
N_{0(n+1)} &= \left\{ \begin{array}{l}
\frac{1}{R} - \frac{p_{1(n)}}{p_{0(n)}} \ln H - p_{1(n)} \ln (1 - p_{1(n)}) \ln (1 - p_{0(n)}) \ln (1 - p_{1(n)})
\end{array} \right. \\
N_{1(n+1)} &= \frac{\ln H - N_0 \ln (1 - p_{0(n)})}{\ln (1 - p_{1(n)})}
\end{align*}
\]  \hspace{1cm} (4.10)

Where, \(R = \frac{H}{1 - H (E[N_c]_{n+1} + 1)}\) and \(H = \frac{E[I]_{n+1}}{t_{slot} + E[I]_{n+1}}\).

However, equation (4.8) and (4.9) are not sufficient enough to deduce the number of active nodes once the traffic-class exceeds 2. In [5], it is suggested to count the number of active stations for class \(i\) in real-time from the channel access history overheard in the past \(H_i\) successful transmissions. The value of \(H_i\) is critical to the accuracy of the estimation. A larger \(H_i\) indicates a higher accuracy of estimation but slower reaction to the node changes. Y. Ge [5] suggests selecting \(H_i\) as the largest integer \(k\) to satisfy

\[
\sum_{j=1}^{k} (P_s(i))^j (1 - P_s(i))^{k-j} > \alpha
\]  \hspace{1cm} (4.11)
Where, \( P_i(i) = \frac{p_i}{(1 - p_i) \sum_{j=1}^{P} \frac{N_j p_j}{1 - p_j}} \)

Similarly to the equal case, we use equation (4.7) to eliminate the fluctuations, i.e., \( N_{i(n+1)} = N_{i(n)} \cdot \alpha + N_{temp(i(n+1))} \cdot (1 - \alpha) \).

### 4.3 Renewal of Optimal Transmission Probabilities

With the estimated \( E[I] \), \( E[T_c] \), and \( N_{i(n)} \), we can use the constraints in (3.17), (3.20), and (4.1) to fetch the optimal transmission probability set. We consider two cases here as what we did for the estimation of \( N_i \).

#### 4.3.1 Equal number of stations in all traffic classes

Substituting the constraint (3-1) into the expression of \( E[I] \) (equation (3.17)), we can reform a new equation as:

\[
\prod_{i=1}^{P} (1 - p_{i(n+1)})^{N_i} = \frac{E[T_c]_{n+1}}{E[T_c]_{n+1} + t_{slot}}
\]

(4.12)

With the assumption \( N_{i(n)} = N_{j(n)}\), \((0 < i, j < P, and \ i \neq j)\), the above equation can be further rewritten as:

\[
\prod_{i=1}^{P} (1 - p_{i(n+1)}) = \prod_{i=1}^{P} e^{N_{i(n+1)} \frac{E[T_c]_{n+1}}{E[T_c]_{n+1} + t_{slot}}}
\]

(4.13)

The throughput ratio (equation (3.20)) can be specialized for this case as:

\[
\hat{r}_{0i} = r_{0i} = \frac{E[m_i]}{E[m_0]} \cdot \frac{p_{0(n+1)}(1 - p_{i(n+1)})}{p_{i(n+1)}(1 - p_{0(n+1)})}
\]

(4.14)
Therefore, the transmission probability for a class $i$ station $p_i (i = 1, 2, \ldots P)$, can be uniquely solved with the combination of equations (4.13) and (4.14). Specifically, for the case with two traffic classes, equations (4.13) and (4.14) become:

$$\begin{align*}
(1 - p_{0(n+1)})(1 - p_{1(n+1)}) &= \left(\frac{N_{0(n+1)}E[T_{c,n+1}]}{E[T_{c,n+1}] + t_{slot}}\right)^2 \\
\frac{p_{1(n+1)}}{N_{0(n+1)}P_{0(n+1)} + r_{01}N_{1(n+1)}(1 - p_{0(n+1)})}
\end{align*}$$

(4.15)

Finally, we have $p_0$ and $p_1$ calculated:

$$\begin{align*}
p_{0(n+1)} &= \frac{1}{2} \cdot (2 + \frac{A}{r_{12}} - A - \sqrt{(1 + \frac{A}{r_{12}} - A)^2 - 4(2 - A)}) \\
p_{1(n)} &= \frac{N_{0(n)}P_{0(n)}}{N_{0(n)}P_{0(n)} + r_{01}N_{1(n)}(1 - p_{0(n)})}
\end{align*}$$

(4.16)

where $A = \frac{N_{0(n+1)}E[T_{c,n+1}]}{E[T_{c,n+1}] + t_{slot}}$.

### 4.3.2 Nonequal number of stations in different traffic classes

For the case that there are two traffic classes and each traffic class has a different number of active STAs, we can express the equation (4.12) as:

$$(1 - p_{0(n)})^{N_{0(n+1)}} (1 - p_{1(n)})^{N_{1(n+1)}} = \frac{E[T_{c,n+1}]}{1 + E[T_{c,n+1}]} = A.$$

(4.17)

Considering that there are 2 (or $n$ in a general case) unknown transmission probabilities on the left side of equation (4.17), the constraint (3.20) provides one more (or $n-1$ more in a general case) equation(s). Together there are two (or $n$ in a general case)
equations and two (or \( n \) in a general case) unknowns. For the two-class with nonequal station case, the equation (3.20) can be rewritten as:

\[
E[m_0] \cdot \frac{N_0}{N_1} \cdot \frac{p_{0(n+1)}(1 - p_{1(n+1)})}{p_{1(n+1)}(1 - p_{0(n+1)})}
\]  

(4.18)

It is difficult to derive the close form solution of the new transmission-probability set \( \{ p_i \} \) from the previous equations. Alternatively, we develop the following numerical iterations to approximate the solutions on demand.

1) Initially set \( p_{0(n+1)} = p_{0(n)} \), and let \( p_{\text{min}} = 0 \), and \( p_{\text{max}} = 1 \);

2) Calculate \( p_{1(n+1)} \) according to equation (4.13);

3) Compare the values of the left and right side of the equation (4.13) using \( p_{0(n+1)} \) and \( p_{1(n+1)} \). If the difference between the left and right side is smaller than 0.001, then skip the loop below. Otherwise, do the following:

a. If \( \text{Left} > \text{Right} \), let \( p'_{\text{min}} = p_0 \), \( p_0 = (p_0 + p_{\text{max}})/2 \), and \( p_{\text{min}} = \max(p_{\text{min}}, p'_{\text{min}}) \);

b. If \( \text{Left} < \text{Right} \), let \( p'_{\text{max}} = p_0 \), \( p_0 = (p_0 + p_{\text{min}})/2 \), and \( p_{\text{max}} = \min(p_{\text{max}}, p'_{\text{max}}) \);

c. Go back to 2).

4.4 Mapping the p-persistent Transmission Probabilities into 802.11 MAC Contention Window Sizes

In the legacy IEEE 802.11 MAC protocol, the contention widow size is updated according to the binary exponential backoff algorithm, where the initial contention
window size is $CW_{\text{min}}$, and it is doubled after each detected collision till its value reaches $CW_{\text{max}}$. If the network works at the optimal status, the number of collisions will be very low, and the contention window size will remain close to the minimum value.

As mentioned in chapter II, a $p$-persistent MAC protocol differs from the DCF protocol only in the selection of the backoff interval. It can closely approximate the standard protocol that operates with the same average size of backoff window. Thus, the class-$i$ optimal $p_i$ in the $p$-persistent IEEE 802.11 MAC protocol can be converted to the class-$i$ contention widow size in the DCF IEEE 802.11 MAC protocol by setting both $CW_{\text{min}}$ and $CW_{\text{max}}$ to

$$CW_i = \text{floor} \left( \frac{2}{p_i} - 2 \right),$$

which has been verified via the Markov chain model in [5].

The newly optimal $CW_i(i = 1, 2, \ldots, P)$ will replace the previous value at the very beginning of the next virtual transmission period. Figure 4.2 summarizes the procedure of our adaptive $p$-persistent based 802.11 MAC scheme.

Throughout the updating cycle, the network can remain aware of its configurations and the traffic load in a timely manner and then make adjustments on the transmission probability for each traffic class correspondingly. By doing so, we can ensure that the network always operates around the near optimal status (i.e., the time spent on the idle stage is equal to the collision cost and the target throughout ratios are maintained), even though the network conditions changes dynamically. In order to test
the efficiency of our adaptive PMAC scheme, extensive simulation experiments in ns-2 have been conducted. The simulation results are presented in the next chapter.
CHAPTER V

PERFORMANCE EVALUATION AND SIMULATION RESULTS

In this chapter, we investigate the performance of the proposed adaptive scheme under different scenarios by simulations in ns-2. The simulation results are analyzed and presented.

5.1 Simulation Environments

All the simulation experiments are conducted in Network Simulator ns-2 (version 2.26) [28]. The simulation models have been built by revising the open-sourced IEEE 802.11e EDCF simulation model developed by the Telecommunication Networks Group (TKN) [29], [31], [32] and the simulation model developed in [5]. In the simulations, each wireless station is able to operate the 802.11b IEEE standard MAC protocol. All of the packets have the same size (i.e., $x_0 = x_1 = 500$ bytes). The smoothing factor $\alpha$ is set to 0.9. The IEEE 802.11 MAC layer parameters used in our simulations are listed in Table 5.1.

The simulation studies begin with the scenario by assuming that the number of active stations remains constant throughout the entire simulation, followed by the scenario in which we allow the stations to dynamically join or leave the network during...
the middle of simulation. The measurements on the following six metrics are collected for each simulation run: channel throughput, throughput ratios, and station transmission probabilities, estimated number of active STAs, $E[I]$ and $E[T_c]$. Given a certain network configuration, the theoretical optimal transmission probabilities for the stations belonging to the different traffic classes and the theoretical maximum channel throughput can be calculated based on the analytical models presented Chapter II and Chapter III. The theoretical values are used as benchmarks to evaluate the accuracy of the simulation results in this chapter.

Table 5.1 Network Configuration (802.11b)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{slot}}$</td>
<td>20µs</td>
</tr>
<tr>
<td>SIFS</td>
<td>10µs</td>
</tr>
<tr>
<td>DIFS</td>
<td>50µs</td>
</tr>
<tr>
<td>Data Rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>PLCPDataRate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>PreambleLengthBits</td>
<td>144 bits</td>
</tr>
<tr>
<td>PLCPHdrLength</td>
<td>48 bits</td>
</tr>
<tr>
<td>ACKLengthBytes</td>
<td>14 bytes</td>
</tr>
<tr>
<td>MacHeaderLengthBytes</td>
<td>28 bytes</td>
</tr>
</tbody>
</table>

In the following simulation, the smooth factor $a$ is set to 0.9. For the estimation method of the number of active stations by observing the channel access history overhead in the past $H_i$ successful transmissions, the parameter $H_{a[i]}$ for class i, is initialized as 100.
5.2 Scenario 1: the number of active stations keeps unchanged

In this scenario, we assume the number of active stations remains constant during the entire simulation. Once the simulation begins, the proposed algorithm adapts the network to its corresponding optimal operating status by fine-tuning the transmission probabilities for different stations towards their respective optimal values. We evaluated the algorithm in the following two cases for this scenario:

Case 1. There is the same number of stations in the two traffic classes, and the desired throughput ratio between the two classes is \( \hat{r} = 2.0 \).

Case 2. The two traffic classes have different number of stations, and the desired throughput ratio between the two classes is \( \hat{r} = 2.0 \).

5.2.1 Case 1: equal number of stations in two classes

In this case, the number of active stations for both traffic classes is set to 20. The adaptive algorithm is evoked at 2.5s due to insufficient data for adaptation during the initial 2.5 seconds.
From Figure 5.1, we can see that it takes about 5s for the throughput to increase to 3.5 Mbps after the adaptive algorithm initiates; and it remains constant thereafter.

Figure 5.1 Channel Throughput: Scenario 1 Case 1

Figure 5.2 Throughput Ratio: Scenario 1 Case 1
The throughput ratio indicated in Figure 5.2 is near the preset value 2.0.

In Figure 5.3, the solid curves indicate the trace of the updated transmission probabilities. $p_0$ represents the transmission probability for the stations in class 1, and $p_1$ represents the transmission probability for the class 2 stations.

![Figure 5.3 Station Transmission Probabilities: Scenario 1 Case 1](image)

The simulated values obviously have some fluctuations due to the estimation methods. However, the average transmission probability for each class is very consistent with the theoretical values (0.0111 vs. 0.0103, 0.0056 vs. 0.0052).
Similar to the simulated transmission probabilities, the estimated number of stations \( N_i \) in Figure 5.4 also experiences certain fluctuations, which are caused by the fluctuations of the measurements that are used to estimate the station number. Despite of the fluctuations, its average value is centered on the actual number 20.

![Simulation Results](image)

**Figure 5.4 Estimation of the Number of Active Nodes: Scenario 1 Case 1**

Figure 5.5 below shows the measurements on \( E[T_c] \) and \( E[I] \) from the simulations. Since the proposed adaptive \( p \)-persistent MAC scheme considers the constraint \( E[T_c] \approx E[I] \) as the condition with which the WLAN channel throughput is near its maximum value, the measurements \( E[T_c] \) and \( E[I] \) will have a direct indication on how well the algorithm works to meet the optimization objective. The simulation results indicate an ideal match between \( E[T_c] \) and \( E[I] \).
5.2.2 Case 2: nonequal number of stations in two classes

The numbers of the active STA for the two traffic classes are $N_0 = 25, N_1 = 15$. As analyzed in chapter III, the estimations on the number of stations in this case are more complicated than in the equal station case. Besides $E[I]$ and $E[T_c]$, the measurements on $E[N_c]$ are also needed for the estimation on the station numbers for the two traffic class cases.

The simulation results show that using the formulas (3.10) in Chapter III to estimate the station numbers can cause big fluctuations, which consequently lead to poor simulation performance. Our investigations show that the fluctuations on $N_i$ estimations are mainly caused by the fluctuations on the measurements of $E[N_c]$. In the following
results, the active number of stations in the two traffic classes is estimated by overhearing the channel history.

![Graph](image)

Figure 5.6 Channel Throughput: Scenario 1 Case 2

The actual channel throughput for this nonequal case is still quite close to its theoretical maximum value 3.607.

And the simulated throughput ratio in Figure 5.7 evidently sticks around at the preset value 2.0 as well.
Figure 5.7 Throughput Ratio: Scenario 1 Case 2

Figure 5.8 Station Transmission Probabilities: Scenario 1 Case 2
In Figure 5.8, the average periodically updated transmission probabilities are centered near the optimal values calculated according to this certain scenario.

Within the 4 seconds at the beginning of the simulation, the adaptive algorithm is not effective, and the transmission probabilities are set to 0.001; after that period, the proposed algorithm updates the transmission probabilities for two classes after each virtual transmission time.

Figure 5.9 shows that the estimated $N_i$ has much less fluctuations than by using formulas (3.10) for estimation. However, the average values for $N_0$ and $N_1$ are a little bit less than the actual numbers.

![Graph showing estimation of the number of active nodes](image)

Figure 5.9 Estimation of the Number of Active Nodes: Scenario 1 Case 2
As for the comparison between $E[I]$ and $E[T_c]$ in Figure 5.10, it’s noticeable that the average consecutive idle time $E[I]$ is much closer to the average collision cost $E[T_c]$ than what has been observed in case 1. The throughput and throughput ratio are both very close to the desired values.

![Figure 5.10 Comparisons between $E[I]$, $E[T_c]$: Scenario 1 Case 2](image)

From the simulation results, we found that the fluctuations of the $N_i$ estimations have a great impact on the performance of the adaptive PMAC algorithm. The algorithm, on the other hand, is quite robust against the accuracy of the $N_i$ estimation. And the one-class simulation studies shown in [4] also indicate the adaptive PMAC scheme can tolerate certain inaccuracy on the number of station estimation.
5.3 Scenario 2: the number of active stations changes during the simulation

The simulation results in scenario 1 show that the proposed MAC scheme can effectively adapt the network to the optimal operating point and remain at the optimal point thereafter if the number of active stations remains constant. In reality, a network always operates in a dynamic environment, where stations join and leave the network randomly. Thus, the MAC scheme will need to constantly adapt the network to the corresponding new optimal points when change occurs. We create a scenario where the number of active STAs changes in the middle of the simulation and observe the networks’ reactions to the change by using the proposed algorithm. Similarly, we also consider two cases in this scenario.

Case 1. There is the same number of stations in the two traffic classes, and the desired throughput ratio between the two classes is \( \hat{r} = 2.0 \).

Case 2. The two traffic classes have different number of stations, and the desired throughput ratio between the two classes is \( \hat{r} = 2.0 \).

5.3.1 Case 1: equal number of stations in two classes

For case 1, we set \( N_0 = N_1 = 10 \) in the first 50s. Both \( N_0 \) and \( N_1 \) increase to 30 at the 50\(^{th} \) second and stay there till the end of the simulation. The throughput ratio between two traffic classes (\( \hat{r} \)) is 2.0.

In the first half of the simulation, the network behaves similarly to what saw in scenario 1, case 1. The throughput stays very close to the maximum value and the throughput ratio centers around 2.0. At the 50\(^{th} \) second, the network experiences a sudden
change in the number of active stations in both traffic classes. The station number changes from 10 to 30 for both classes. This change leads to a total of 60 stations to compete for the common channel access in the network.

Figure 5.11 Channel Throughput: Scenario 2 Case 1

In Figure 5.11, the throughput in the second 50s fluctuates more than that in the first 50s. Because there are more stations competing for the channel access in the second half of the simulation. Even though we have not theoretically proved that more stations competing for the common channel access can lead to more statistical fluctuations in the networks.

The adaptive algorithm first detects that $E[I]$ deviates from $E[T_c]$ and also detects that the throughput ratio between two classes is significantly farther away from the preset value 2.0. All of these changes will be reflected in the network real time
measurements, which are used to adapt the station transmission probabilities to the new values.

![Figure 5.12 Throughput Ratio: Scenario 2 Case 1](image)

From Figures 5.11 and 5.12, the throughput and the throughput ratio deviate from the desirable values due to the sudden change in the stations. However, both of them can re-approach the desired levels after an adaptive period by using the proposed adaptive algorithm.

In Figure 5.13, although the simulated values have some fluctuations, the mean values for both $p_0$ and $p_1$ are close to the theoretical values during the entire simulation time. It also shows that the adaptive algorithm does adapt the transmission probabilities very effectively when change occurs in the network.
Figure 5.13 Station Transmission Probabilities: Scenario 2 Case 1

Figure 5.14 Estimation of the Number of Active Nodes: Scenario 2 Case 1
Figure 5.14 indicates the estimations on the number of active stations respond to the actual change very well. The average number centers around 10 in the first 50s. The number centers around the actual number 30 but with more fluctuations in the second 50s.

The following Figure 5.15 shows that $E[I]$ is quite close to $E[T_c]$ in both the first half and the second half 50s, except during the short adaptation period.

![Figure 5.15 Comparisons between $E[I]$, $E[T_c]$: Scenario 2 Case 1](image)

From the results, we can conclude that our proposed PMAC algorithm is capable of capturing the network dynamics and effectively adapting the network to the new optimal operating points.
5.3.2 **Case 2: nonequal number of stations in two classes**

We continue to examine the performance on the nonequal station number case for scenario 2. In this case, $N_0$ increases from 10 to 30, while $N_1$ decreases from 20 to 10, all happening at 50s. The throughput ratio is still 2.0. This nonequal case of changing $N_i (i = 0,1)$ is the most complicated, yet it is also the most realistic one.

![Figure 5.16 Channel Throughput: Scenario 2 Case 2](image)

For the channel throughput in Figure 5.16, similar to the equal $N_i$ changing case, there is an abrupt drop around the 50s when the change occurs for two traffic classes. The total number of stations in the network changes from 30 to 40.

In Figure 5.17, the throughput ratio skyrockets to 9.6 immediately after the changing point; and it goes back to around 2.0 after a short transition time interval.
Figure 5.17 Throughput Ratio: Scenario 2 Case 2

Figure 5.18 Station Transmission Probabilities: Scenario 2 Case 2
As for the transmission probabilities, except the abnormal values during the short transition period near 50s, the mean values of the transmission probabilities center around the theoretically values. It manifests the same changing trend as the previous adaptive equal case does in Figure 5.13, which demonstrates that the proposed algorithm works very well for this most complicated case as well.

![Figure 5.19 Estimation of the Number of Active Nodes: Scenario 2 Case 2](image)

Regarding the estimations on $N_i (i = 0,1)$ in Figure 5.19 the estimated values evidently stick to the actual numbers, even though more fluctuations are observed in the 2$^{nd}$ 50s.
Figure 5.20 shows the similar trend as Figure 5.15 for the equal case does. The measured $E[I]$ and $E[T_c]$ are similar during the entire simulation time, except for several seconds of the transition time right after 50s.

![Figure 5.20 Comparisons between $E[I]$, $E[T_c]$: Scenario 2 Case 2](image)

**5.4 Summary**

The simulation results, according to the previous theoretical analysis, demonstrate that the $p$-persistent version adaptive MAC algorithm works very well for the simple adaptive case, and it is also sufficient to deal with the network dynamics. In the next chapter, we will further discuss the conclusion and the future work.
CHAPTER VI
CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this thesis, an adaptive IEEE 802.11 MAC has been developed and evaluated. The proposed scheme aims to achieve the maximum WLAN channel throughput and to provide QoS differentiations among different services supported in the network. This is achieved by updating the transmission probabilities for the stations that compete for transmissions in a WLAN adaptively based on the real time network measurements. According to the proposed implementation model and the flowchart of the algorithm, we conducted simulation experiments in ns-2 to testify accuracy and evaluate the efficiency of the adaptive PMAC scheme. From the simulation results, we conclude that the proposed scheme can adapt the station transmission probabilities to their desirable values, so that the system throughput can be maintained at its maximum value and the target throughput ratios among different traffic stations can be achieved in a dynamic WLAN environment. The proposed scheme also has a rather low computational complexity, which makes it a suitable choice for real-time implementation.

6.2 Future Work

The proposed algorithm works well for various scenarios. However, we need to notice the assumptions we made to simplify the analysis and the simulation. In a real
network, the packet length may not be the same for all packets. Modifying the proposed adaptive PMAC to solve the hidden terminal problems is also an interesting and important research topic. As we pointed out in Chapter IV, the accuracy of the estimation on the number of active stations greatly affects the efficiency of the adaptive algorithm. Further study on how to improve estimation accuracy on the number of active stations can be conducted. The proposed scheme theoretically works for any \( n \) (\( n > 1 \)) traffic classes. In the thesis, the simulations are set up with the assumption \( n = 2 \). More simulations can be carried out for a higher number (\( n > 2 \)) of traffic classes in order to further evaluate the performance of the proposed scheme.
REFERENCES


