國 立 交 通 大 學

電信工程學系

博 士 論 文

# 應用於WCDMA/WLAN異質網路之乏晰邏輯允諾控制

# Call Admission Control for WCDMA/WLAN Heterogeneous Networks Using Fuzzy Logic Theorem

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中 華 民 國 九十六 年 七 月

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電信工程學系

博士論文

A Dissertation
Submitted to Department of Communication Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in
Communication Engineering
Hsinchu, Taiwan

2007 年 7 月

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## 中文摘要

藉由整合不同無線通訊網路所構成的異質網路（heterogeneous network）是有效提升整體服務容量與品質的方法之一。本篇論文所研究之寬頻分碼多重進接（WCDMA）系統與無線區域網路（WLAN）共存之異質網路，除兩者皆為現今使用最廣泛的通訊標準外，其個別之通訊特性更具有高度的互補性。WCDMA 通訊覆蓋範圍大，支援高速移動通訊服務，並且具備完整之信令架構與核心網路，提供無線資源管理極佳的平台，唯其網路建置成本高，而且面對日益精緻之多媒體服務，但各通道之最高資料傳輸速率仍不足；雖有如多用戶偵測（multiuser detection）等進階機制可提昇系統容量，但所需的高運算量仍是實際必須考量之處。而 WLAN 則具備高傳輸速率以及網路建置成本低之優勢，但一般覆蓋範圍較小且多為區域性，再加上行動服務支援度低，因此無法有效提供行動用戶無縫式之寬頻服務。由此可知，在設計 WCDMA/WLAN 異質網路資源管理機制時，可針對彼此之特性截長補短，提供更優良的寬頻行動網路服務。

允諾控制（admission control）是 WCDMA/WLAN 異質網路資源管理中極為重要的管理機制之一。面對使用者所提出的連線與服務品質（QoS）要求，允諾控制必須能有效掌握各個網路之通訊品質狀態以及資源利用之程度，對於行動用戶經由換手（handoff）而產生的連線要求，更必須考慮該原有服務之連續性。因此本篇論文首先提出在 WCDMA 系統中應用多用戶偵測方法時的呼叫允諾控制器設計。利用序列式干擾消除（successive interference cancellation；SIC）而達成多用戶偵測的目的可大幅提昇系統容量，也由於接收訊號經過 SIC 再處理後特性已有改變，主要干擾源將變成來自於鄰近細胞。因此在我們所提出之呼叫允諾控制將鄰近細胞干擾的影響比例提高，並且引進乏晰邏輯技術，針對多變之系統狀態作出最佳之允諾決策。

其次，本篇論文也針對 WLAN 系統提出一結合允諾控制與排程之機制設計，其中針對訊號品質與服務要求，為使用者上下鏈路傳輸安排適當之傳輸機會（transmission opportunity）。另外鑑於 WLAN 中缺乏迅速有效之換手方式，因此我們也提出一套相容於 IEEE 802.11e 標準之快速換手協定（fast handoff protocol；FHP），以消除換手要求封包在競爭傳輸通道時的延遲不確定性，以利於換手預先動作（pro-active）啟動時機的選擇。

最後，本篇論文整合考慮 WCDMA 與 WLAN 共存異質網路中的允諾控制器設計。其中考慮兩系統個別之系統狀態、使用者 QoS 要求、以及使用者移動狀態估測等關鍵量測值，並利用具適應能力之類神經-乏晰推論系統（neural-fuzzy inference system）與 Q-learning 自我學習機制，決定新進使用者或換手使用者連線要求的允諾與否，以及允諾之最適合網路。故此一設計不但具備允諾控制功能，同時也能作為 WCDMA/WLAN 異質網路中的網路選擇（network selection）控制器。

# Call Admission Control for WCDMA/WLAN Heterogeneous Networks Using Fuzzy Logic Theorem

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## Abstract

The heterogeneous network is a type of the most direct and efficient infrastructure to extend the system capacity and service quality for the demanding multimedia environment. In this dissertation, two of the most popular systems, wideband code division multiple access (WCDMA) system and wireless local area network (WLAN) system, are considered to form the heterogeneous network. As the global cellular system, the WCDMA system has almost universal coverage in the world with high-mobility support and comprehensive core networks. But the cost of deployment and insufficient bandwidth for the growing multimedia services are its major disadvantages. WLAN system provides higher data rate to support multimedia services with lower cost, but the smaller service area and lack of complete handoff procedures restrict the mobility services. Hence, WCDMA and WLAN systems are highly complementary to each other. Basing on these features, we develop call admission control (CAC) schemes with fuzzy logic theorem for WCDMA and WLAN systems to achieve quality-of-service (QoS) guarantee and higher system utilization in the heterogeneous networks.

Multiuser detection (MUD) has been discussed and studied for a couple of years. Its impressive increase in capacity has attracted WCDMA systems to consider to adopt this technology. The capacity limit, however, still exists due to other cells' multiple access interference (MAI) in a cellular system. As a result, a CAC scheme is essential to control the number of mobile users from the view of point of MUD. This dissertation proposes an outage-based fuzzy call admission controller with multiuser detection (OFCAC-MUD) for WCDMA systems. The successive interference cancellation (SIC) is used as MUD because it has lower complexity and more suitable for the fading channel with imperfect power control. The OFCAC-MUD determines the new call admission based on the uplink signal-to-interference ratios from home and adjacent cells and system outage probabilities. The OFCAC-MUD possesses both the effective reasoning capability of fuzzy logic system and the aggressive processing ability of MUD. Simulation results reveal that OFCAC-MUD without power control (PC) improves the system capacity by 70.5% as compared to an SIR-based CAC-RAKE with perfect PC. It also enhances the system capacity by 53.9% as compared to an OFCAC-RAKE with perfect PC, by 6.7% as compared to an SIR-based CAC-MUD without PC, and by 12.9% as compared to an OFCAC-MUD with perfect PC, given the same outage probability requirements. Moreover, OFCAC-MUD can prevent the violation of outage probability requirements in the hotspot environment, which is hardly achieved by SIR-based CAC.

For the WLAN systems, we propose an intuitive scheduling and admission control (ISAC) scheme based on hybrid coordination function (HCF) mode in IEEE 802.11e cellular WLAN systems. The ISAC scheme considers admission control, based on not only the quality of service (QoS) required by each application but also the link quality of air interface influenced by the co-channel interference from adjacent cells.

Furthermore, we also propose a fast handoff protocol (FHP) for cellular IEEE 802.11e WLAN systems. The FHP, which is standard compatible, provides a controlled contention period (CCP) designated for handoff requests (HO-REQs), arranges these HO-REQs to contend sequentially in CCP, and proposes a fuzzy adjustment method (FAM) to determine a proper length for CCP. Simulation results reveal that the FHP can significantly decrease the forced termination rate of HO-REQ and enhance the system throughput of contention period for cellular IEEE 802.11e WLAN systems.

Finally, a fuzzy Q-learning admission control (FQAC) mechanism is proposed for WCDMA/WLAN heterogeneous networks in this dissertation. The FQAC consists of dwelling estimation and admissibility estimation to consider the mobility pattern and essential system measures. The dwelling estimation can assess the dwell time length for a mobile user in the reachable subnetworks and output dwelling costs. The admissibility estimation can judge which reachable subnetwork(s) can support the required QoS and output admissibility costs. With Q-learning method, the FQAC can adaptively adjust the actions to output the costs without the knowledge of system state transition probability. In order to minimize the expected maximal impact (cost) of the user's admission request, the decision maker applies the Minimax criterion for these costs and decides the most suitable subnetwork or reject the user request. Simulation results show that FQAC can almost maintain the system QoS because it can appropriately admit or reject the users' admission requests. The dwelling estimation can significantly reduce the number of handoffs, which makes FQAC to have lower handoff blocking probability in those real-time services.

# Acknowledgments

First of all, I would like to express my sincere gratitude to my advisor, Dr. Chung-Ju Chang, for the patient guidance and concern over the research details and methodology. His attentive and professional attitude is always the quintessence of imitation.

I also want to express my appreciation for the crew of my Lab and all my friends. Their assistance is always helpful and warm.

This dissertation is dedicated to my parents. I am deeply indebted to them for their encouragement and cherish. Their wholehearted support is the prime momentum on my road of progress.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1 Motivation

Internet has driven developments of networks and applications. People are more and more accustomed to acquire or share content information on Internet. Demands for high speed and multimedia services in wireless communications are growing rapidly. As the prevalence of Global System for Mobile Communications (GSM), which has shown the convenience in mobility, the requirements of the mobile Internet are also increasing. The GSM system, also called the second generation (2G) system, is designed for the circuit switch services, mainly voice services. In order to support Internet multimedia services, advanced wireless communication specifications are exceedingly desired. Both telecommunication and data-communication parties have been aware the trends, and their aggressive activities of global standardizations have brought the buds of truly broadband wireless communications. In the cellular systems, the General Packet Radio Service (GPRS) were introduced by the end of last century. It is an extended packet switch version over GSM construction to support data services such as wireless application protocol (WAP), short message services (SMS), and etc. But its limited bandwidth restricts the types of services. Thus several telecommunication standard bodies established the 3rd Generation Partnership Project (3GPP) in 1998 to standardize the third generation (3G) mobile radio networks with code division multiple access (CDMA) technology to provide multimedia wireless services. Yet the maximum data rates of 3G cannot meet the increasing demands of services, and should use High Speed Packet Access (HSPA) [1] for both downlink and uplink to provides a possible solution for rapid transmission.

On the other hand, the party of data-communications also aims the profitable campaign of broadband wireless communications. The most successful standards in recent years are IEEE 802.11 Wireless Local Area Network (WLAN) [2] and the amendments. The development of the WLAN system is growing rapidly because it uses unlicensed spectrum and provides high-speed wireless access in a small region. By using WLAN, many local area network (LAN)-based deployments can be simplified and the usage of networks would be very flexible. Users can access the network at any place within the coverage of WLANs. All they have to do is install the WLAN adapters properly. Therefore the widely deployed WLAN access points (APs) become the most common options of Internet ingress channels in the buildings, chambers, homes, indoor hotspots, or even at road sides. The WLAN adapters almost become the standard equipments in the personal computers now. Despite the poor mobility, WLAN provides sufficient bandwidth for the activities on Internet.

The enormous popularity of WLAN attracts 3GPP's attentions. The latest release of 3GPP has specified the direction on WCDMA system to 802.11 WLAN interworking [3,4]. which tries to combine both indoor and outdoor high speed communication systems to offer a comprehensive multimedia communication platform and provide complete service coverage in future communication systems. Such heterogeneous networks are the most practical architecture to satisfy the variety of broadband service requirements. With different coverage ranges and physical designs, WCDMA and WLAN have their own features in transmissions. WCDMA, with lower data rate, covers larger area and has a superior support in mobility; WLAN supports higher data rates but smaller coverage and lower mobility. The combination of these two systems could bring their advantages together, and mobile users would have more chances to access more suitable networks for their services.

From the standard development point of view, WCDMA/WLAN heterogeneous networks are indeed the most notable systems to provide broadband multimedia services. The major advantage of the heterogeneous network is that system can select the better networks and service modes to serve the users according to locations, quality of service (QoS) requirements, channel conditions, and etc. For example, when a user is in a building, in which the WLAN has been deployed densely, the system will tend to assign a WLAN channel for the user. If the user is moving, the system will automatically switch the connection to WCDMA system to support better mobility. The concept of network selection in heterogeneous networks is equivalent to the admission control of these networks. The admission results from these networks can be coordinated property and the most suitable network can be determined. Simple admission controls for WCDMA and WLAN can help systems to initiate a new access setup in either WCDMA or WLAN, but they cannot choose which system is a better one. Therefore in this dissertation, advanced call admission control (CAC) schemes are investigated and designed in WCDMA/WLAN heterogeneous networks. By means of fuzzy logic theorem, the CAC for both WCDMA and WLAN systems may take more realistic and time-variant system states into consideration to achieve high system utilization while quality of service (QoS) guarantee.

## 1.2 Paper Survey

Call admission control (CAC) is one of the most important issues in the radio resource management. It is the first checkpoint of the wireless systems to maintain the system QoS and prevent systems' instability due to overloading. In order to govern the entrance of mobile users effectively, information of system states and user requirements are essential. Therefore CAC designs usually emphasize the types of information of system states and the approaches to check if the system's resource could fulfill user requirements. As the category of services and user mobility increases, CAC has to face the challenge to catch the unsettled system states due to multipath, shadowing, noise, interference, etc. [5]. Especially when some advanced transmission technologies are used, such as multiuser detection (MUD) and orthogonal frequency division multiple access (OFDMA), the design of CAC is more critical to take advantage of spectrum efficiency and achieve high system utilization.

Since WCDMA system adopts the code division multiple access (CDMA) technology, the system capacity is interference constrained and there is not a clear boundary of acceptable number of users. Guérin, etc. [6] and Gilhousen, etc. [7] provided mathematical approaches to evaluate CDMA capacity. MUD [8] is a kind of effective receiver to increase the capacity of WCDMA systems. It tries to suppress the local multiple access interference (MAI), and the signal can be treated as the single user communications, which is also the ideal result of MUD. As a result, the interference from other users will not be the constraint of the capacity. The concept could be achieved by two means of *Linear Detection* and *Interference Cancellation* [9,10]. The former is to detect the correlations among arbitrary two users' signals. According to the correlations, some kind of compensation method can help to reduce the MAI. The later is to regenerate the transmitted signals of every user and then perform signal cancellation procedure. Verdú [11] proved that the MUD with maximum-likelihood sequence detection (MLSE), which is a kind of linear detection, is the optimal solution. But its complexity is too high to be feasible. The linear detection provides another way to approach the optimal result of MUD, which forms a correlation matrix among all user and uses *linear mapping approach* to compensate the MAI. As the number of user increases, the correlation matrix, however, could grow rapidly and the computation of MAI compensation would be very high [12]. To solve this problem, the *Decorrelating Detector* algorithms proposed early in [13] and [14] are adopted to reduce the computation of correlation matrix. Xie, etc. [15] also mentioned the *Minimum Mean-Squared Error Detector* to reduce the computation complexity. Lupas and Verdú [16] proposed the analysis about near-far resistance in MUD.

As compared to the linear detectors, the interference cancellation is more feasible, but the performance is suboptimal because it is very hard to precisely estimate the signal for cancellation. Two types of interference cancellation in MUD, the successive interference cancellation (SIC) [17] and parallel interference cancellation (PIC) [18], are considered to be feasible in the communication system today. Both of them try to estimate the interference and cancel it. The difference is the structure of the order of cancellation stages [9, 10]. The precision of the interference estimation almost determines the performance of SIC and PIC.

The primitive SIC and PIC are also called "hard" SIC and PIC because they intend to obtain the hard tentative decision of signal bits first and then regenerate the transmission waveforms as the estimated interference. A wrong decision will cause the doubling of the interference, and the performance will be worse when the multistage of SIC or PIC is used because of the error propagation [19]. To avoid this problem, "linear" SIC and PIC are mentioned in [20–22], which use the soft tentative decisions as the estimated interference. Each CS even does not need to know the signal amplitude and the phase shift, which are essential in the hard SIC and PIC. The performances of the linear SIC and PIC are shown in [20, 21, 23], and the results are better than hard SIC and PIC.

The performance of SIC and PIC are determined mainly by the cancellation stages If the cancellation stages can subtract the precise information of the interference, the system will perform more similar to the single user case. In the uplink of code division multiple access (CDMA) system, the issue of power control (PC) is very important for conventional receiver and it is known that the perfect result is to achieve the equal received power of every user. In the cases of hard SIC and PIC, the conventional receivers (RAKE or matched filter) are used to obtain the tentative signal bits, so the PC will directly effect the accuracy of those tentative results. This is similar in the case of linear SIC and PIC.

In addition to the advanced transmission technologies, multiple systems interworking is also an emerging direction to increase the overall system capacity. Such interworking infrastructure would establish a heterogeneous environment of wireless networks. Their heterogeneous properties are the key points of successful interworking. As the evolution of 2G, WCDMA system has the property of nearly universal accessibility. The system also has complete handoff/roaming infrastructure with mobility support. Its security management and charging regime are robust to sustain the reliable operations. Lower bit rate and higher cost are the major drawbacks. On the other hand, WLAN system has the features including high bit rate, hot-spot coverage, and lower cost. But the poor mobility support hinders its developments in mobile applications. It can be found that WCDMA and WLAN systems are mutually complementary. Therefore 3rd Generation Partnership Project (3GPP) launches several technical specifications to establish the standards of WCDMA/WLAN interworking [3, 4, 24–26]. Generally, there are two architectures for WCDMA/WLAN interworking: *tightly-coupled* and *loosely-coupled* architectures [27]. In tightly-coupled architecture, WLAN router is connected to a serving GPRS support node (SGSN) as an alternative radio access network. In loosely-coupled architecture, WLAN is connected to a gateway GPRS support node (GGSN) as a separate network. WCDMA and WLAN networks could be managed by the radio network controller (RNC) of WCDMA systems in both architectures, thus mobile users can require for access through base stations (BSs) or access points (APs).

There are two critical issues in WCDMA/WLAN interworking: the vertical handoff procedure and the network selection method. Vertical handoff means the handoff procedure between WCDMA and WLAN systems [28, 29]. These two issues are directly related to the design of CAC in the heterogeneous networks because the trigger criteria of vertical handoff and the conditions of network selection are usually the baselines of CAC for the destination or the selected network. Several researches have been proposed for vertical handoff and network selection. Yilmaz, etc. [30] proposed a geographical-based method, When the WLAN's beacon strength is higher than a pre-defined threshold, the vertical handoff procedure from WCDMA to WLAN would be performed. It provides a simple and low-cost functionality, but there would be too many unnecessary handoffs if the beacon strength fluctuates across the threshold. Park, etc. [31] proposed a signal strength-based method for vertical handoff between cellular networks and WLANs. The strengths of pilot and beacon are compared to decide which network is better. Chan, etc. [32] proposed a utility-based method. The average data rates are used to formulate the utility functions, which represent the satisfaction degree of mobile users. Without considering the physical channel effects, the proposed market model was used to solve the total utilities maximization problem for all networks to make the network selection decision. These mentioned researches, however, do not consider user mobility and more realistic system conditions such as channel fading, QoS guarantee, or optimized system utilization. Hence there still exist room of improvement in vertical handoff, network selection and call admission for WCDMA/WLAN heterogeneous networks.

## 1.3 Dissertation Organization

In this dissertation, we discuss the call admission control of multimedia services with QoS guarantee in WCDMA/WLAN heterogeneous network. We first consider the admission control issues in WCDMA and WLAN systems. And the admission control for mobile users with joint considerations of WCDMA/WLAN heterogeneous environment is presented finally.

In Chapter 2, an outage-based fuzzy call admission controller with multiuser detection (OFCAC-MUD) for WCDMA systems is introduced. It is the admission control of the cellular part in heterogeneous networks. Successive interference cancellation (SIC) is chosen as the MUD because it has better performance in the fading channel without perfect power control. SIC MUD can eliminate the intra-cell interference, so the inter-cell interference eventually becomes the dominant factor in CAC. To make accurate admission decisions, the OFCAC-MUD considers the worst signal-to-interference ratio (SIR) in home cell, the worst SIR in adjacent cells, and system outage probabilities at outputs of SIC MUDs. With fuzzy technology and an appropriate fuzzy rule base from the expert domain knowledge, the OFCAC-MUD can improve system utilization while maintaining QoS guarantee of all existing mobile users. requirements by constructing an appropriate fuzzy rule base based on the expert domain knowledge.

In Chapter 3, we present an intuitive scheduling and admission control (ISAC) with fast handoff protocol (FHP) for cellular IEEE 802.11e WLAN systems. It contains the admission control of the WLAN part in heterogeneous networks. The WLAN's QoS basic service sets (QBSSs) are cellularized, which is the simplest way to extend the coverage of WLAN services. In order to provide QoS guarantee for a mobile user, the ISAC will calculate the transmission opportunity (TXOP) of the requesting mobile user, and examine if there is sufficient room in the point coordination function (PCF) duration for the TXOP. Besides, IEEE 802.11 standards and the amendments do not consider the seamless handoff problem. Therefore we also proposed a FHP to provide a reliable method for the contention of handoff requests. By means of reserving time duration, the controlled contention period (CCP), for handoff requests, the uncertainty of handoff latency due to access contention in the WLAN system can be eliminated. Meanwhile, a fuzzy adjustment method (FAM) is proposed to adjust the period of CCP intelligently. It can help FHP to increase the CCP utilization and minimize the impact for other contention-based services.

In Chapter 4, a fuzzy Q-learning admission control (FQAC) for WCDMA/WLAN heterogeneous networks is introduced. The FQAC consists of the dwelling estimation, the admissibility estimation, and the decision maker. The dwelling estimation will evaluate the moving status of the mobile user and generate the dwelling cost for every WCDMA or WLAN network near the mobile user. The admissibility estimation considers the measures of system states and QoS requirements of mobile users, and generate the admissibility cost for every WCDMA or WLAN network near the mobile user. Both dwelling and admissibility estimations adopt fuzzy Q-learning (FQL) method to achieve automatic on-line learning for FQAC. With FQL, the correlation between system state and cost generation can be adaptively adjusted. According to the costs, the minimax theorem is adopted in the decision maker, and the ultimately chosen subnetwork is that with the minimal cost among all possible maximal costs. Finally, conclusions and future work are presented in Chapter 5.

# Chapter 2

# An Outage-Based Fuzzy Call Admission Controller with Multiuser Detection for WCDMA Systems

## 2.1 Introduction

Wideband code division multiple access (WCDMA) systems adopt the spread spectrum technology to achieve higher spectrum efficiency for wireless communications [33]. However, they exist multiple access interference (MAI) affecting the system capacity. If receivers in WCDMA systems can reduce MAI when detecting the signal of interest, the capacity will be markedly increased. Accordingly, methods of multiuser detection (MUD) for receivers in WCDMA systems are proposed.

Verdú [11] proposed an optimal MUD solution, which used a maximum likelihood sequence (MLS) detector. Unfortunately, this method is too complex to be practical. Many simplified or suboptimal detectors have been developed and improved [9, 10].

Usually, the suboptimal detectors are classified into two categories: linear detection and interference cancellation [10]. Interference cancellation in uplinks represents an important direction of MUD development because it is highly feasible in the base station (BS). There are two basic constructions of cancellations: successive interference cancellation (SIC) and parallel interference cancellation (PIC). The strategy of SIC, shown in Fig. 2.1, is to discriminate the messages (bits) of other users in series, regenerate the transmitting waveforms, and subtract them from the originally received waveform. PIC is similar to SIC, except in that the regenerated messages are subtracted simultaneously. The advantage of the PIC is its fast process speed, but its complexity makes its implementation difficult. The performance of SIC and PIC was analyzed in [9, 10, 20, 34–38]. According to the results in [10, 20, 34, 38], SIC performs better than PIC in the fading channel without power control (PC). Also the hardware requirement of SIC is fewer than that of PIC. Therefore, this dissertation considers SIC MUD for WCDMA systems.

Generally speaking, the MAI of users at home cell plays a major role in determining the communication quality and the system capacity for WCDMA systems. When the WCDMA system adopts SIC MUD for receivers, the SIC MUD will help to mitigate the negative influence of the home cell interference when detecting the signal of interest. As a result, the admission of a new call request will cause the influence of interference more on existing calls in adjacent cells than on existing calls at home cell. Thus, the design of call admission control in WCDMA system using MUD would be different from traditional ones and should lay emphasis more on adjacent cell interference than on home cell interference.

On the other hand, intelligent techniques, such as fuzzy logic techniques, have been proven to be capable for dealing with nonlinear and time-varying systems, which are

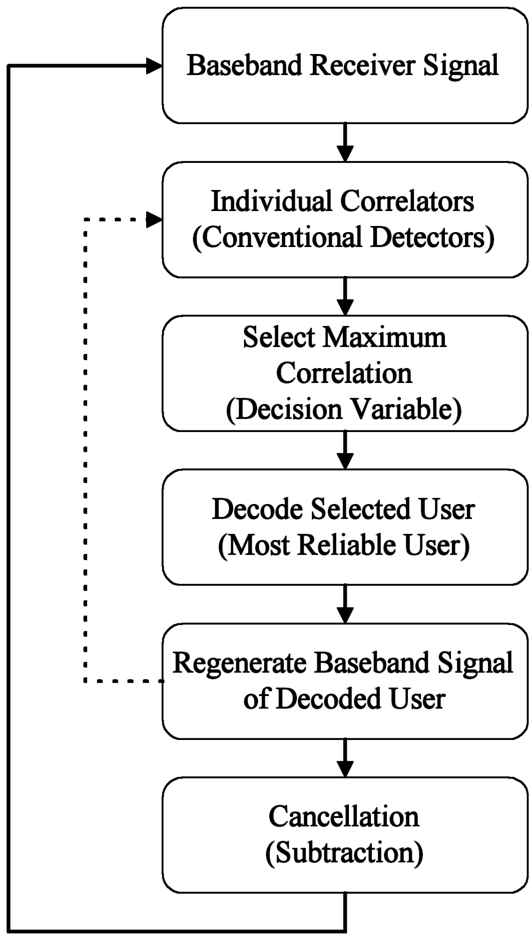


Figure 2.1: The strategy of SIC

difficult to analyze [39]. Results also show that such intelligent computations produce better performance than parametric models of dynamic and complicated systems. As noted, wireless channels could vary due to several factors such as channel fading, interference, noise, etc. The traffic controller for wireless communications should adopt intelligent techniques to adapt to changes of channels so as to improve system utilization.

Therefore, in the chapter, an outage-based fuzzy call admission controller with multiuser detector (OFCAC-MUD) is proposed for WCDMA systems. The OFCAC-MUD makes call admission decision by considering the uplink worst signal-to-interference ratios (SIRs) from not only home cell but also adjacent cells and system outage probabilities at outputs of SIC MUDs. It can improve system utilization under the constraint of quality of service (QoS) requirements by constructing an appropriate fuzzy rule base based on the expert domain knowledge. Simulation results indicate that OFCAC-MUD achieves the system capacity more than the SIR-based CAC under the same QoS requirements. It is found that PC may not be essential for SIC MUD. Also, when the locations of users are uniformly distributed over cells, the capacity of OFCAC-MUD without PC, in satisfying the outage probability criteria, is improved by 70.5% over that of SIR-based CAC-RAKE with perfect PC. When the system is operated in an extremely unbalanced hotspot environment, OFCAC-MUD can still fulfill the QoS requirements of the outage probability, while SIR-based CAC-RAKE violates.

In the following sections, the system model of SIC MUD and the design of OFCAC-MUD will be presented. Section 2.2 briefly introduces SIC MUD and describes the system model. Section 2.3 presents the OFCAC-MUD for WCDMA cellular systems. Section 2.4 shows simulation results and discusses the advantages and disadvantages

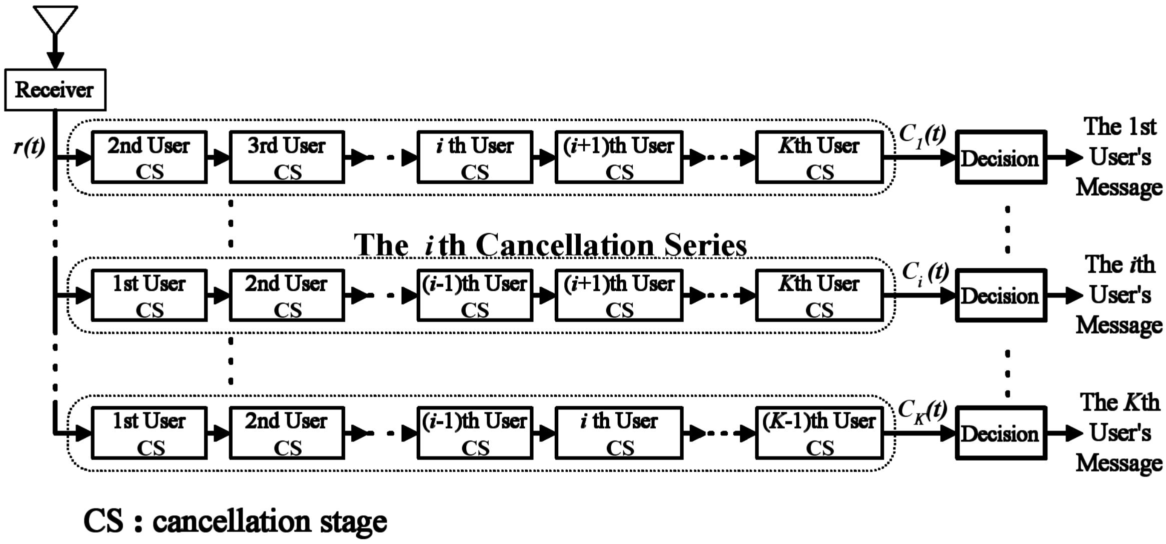


Figure 2.2: A typical SIC MUD for $K$ users

of the OFCAC-MUD design, as compared to SIR-based CAC-MUD and FCAC-RAKE (FCAC with the RAKE receiver). Conclusions are finally made in Section 2.5.

## 2.2 SIC MUD and System Model

Figure 2.2 depicts a typical SIC MUD for $K$ users [20, 34, 38]. Each cancellation stage (CS) in the cancellation series consists of RAKE receivers, a maximal power selector, a signal regenerator, and a subtractor. In the CS, the input signal is firstly passed through the RAKE receivers to detect individual signals of all users. Then the signal with the maximal power will be selected, and the signal regenerator reproduces its original signal according to the carrier frequency, the phase, the amplitude, and the delay profile. Finally, the subtractor will subtract the reproduced signal from the input signal of the CS. The order of CSs in SIC MUD are sorted according to the received powers of users; the first CS cancels the signal of the user who has the largest received power, and so on.

Let $r(t)$ be the baseband received signal at time $t$, which can be expressed as,

$$r(t) = \sum_{k=1}^{K} [S_k(t)a_k(t)] + I_{OC}(t) + n(t), \qquad (2.1)$$

where $S_k(t)$ represents the signal transmitted by the $k$th user; $a_k(t)$ is the activity factor of the $k$th user, $a_k(t) \in \{0, 1\}$; and $I_{OC}(t)$ and $n(t)$ represent the aggregated MAI of the other cells and the AWGN channel noise, respectively. The SIC MUD will generate a signal at the output of the $i$th cancellation series for the $i$th user, $C_i(t)$, $1 \le i \le K$, given as,

$$C_i(t) = r(t) - \sum_{\substack{k=1 \\ k \neq i}}^{K} \hat{S}_k^{(i)}(t)\hat{a}_k^{(i)}(t), \qquad (2.2)$$

where $\hat{S}_k^{(i)}(t)\hat{a}_k^{(i)}(t)$ is the signal regenerated by the $k$th CS. The $C_i(t)$ will be sent to the OFCAC-MUD for further processing.

Figure 2.3 presents the system model for OFCAC-MUD, which contains four functional blocks - (A) system outage probabilities estimator, (B) home cell worst SIR estimator, (C) adjacent cell worst SIR estimator, and (D) OFCAC-MUD. Blocks (A), (B) and (C) generate system performance parameters, which will be used as linguistic variables for block (D).

### 2.2.1 *System Outage Probabilities Estimator*

The system outage probabilities estimator generates two kinds of home cell's system outage probability, long-term and short-term outage probability, denoted by $P_{O,L}$ and $P_{O,S}$, respectively. The outage probability is defined as $Pr\{\text{SIR} < \text{SIR}^*\}$, where SIR is provided by the home cell worst SIR estimator described in the next subsection, and SIR$^*$ is the SIR threshold set by the system. Short and long sliding windows are used to collect the SIR values of every user. Generally, the short-term outage probability reflects the instant fluctuations of system traffic, while the long-term outage

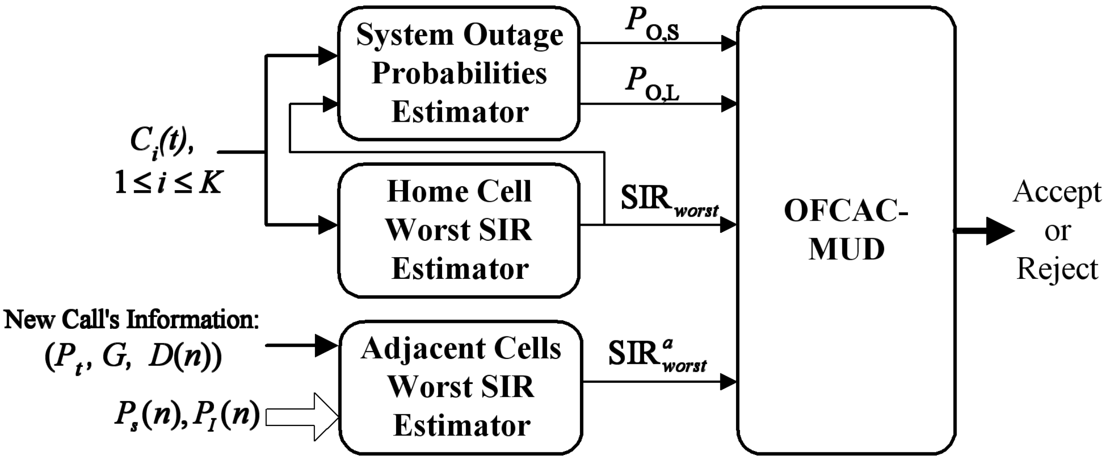


Figure 2.3: The system model for the OFCAC-MUD

probability indeed represents the average QoS of the system traffic. Traffic may violate the short-term outage criterion occasionally, but still satisfy the long-term outage criterion.

### 2.2.2 *Home Cell Worst SIR Estimator*

The home cell worst SIR estimator produces the smallest SIR among all users at home cell, denoted by $\mathrm{SIR}_{worst}$. It first regenerates the $i$th user's signal, $\hat{S}^{(i)}(t)\hat{a}^{(i)}(t)$, from $C_i(t)$ provided by the $i$th cancellation series of SIC MUD, $1 \le i \le K$. Then it derives the overall effective MAI of the $i$th user, $I^{(i)}_{eff}(t)$, by,

$$I^{(i)}_{eff}(t) = C_i(t) - \hat{S}^{(i)}(t)\hat{a}^{(i)}(t). \tag{2.3}$$

The signal-to-interference ratio (SIR) of the $i$th user, $\mathrm{SIR}^{(i)}$, can be yielded as,

$$\mathrm{SIR}^{(i)} = \frac{\int_T (\hat{S}^{(i)}(t)\hat{a}^{(i)}(t))^2 dt}{\int_T (I^{(i)}_{eff}(t))^2 dt}, \tag{2.4}$$

where $T$ is a unit time interval. Consequently, the $\mathrm{SIR}_{worst}$ at home cell can be obtained by,

$$\mathrm{SIR}_{worst} = \min_i \{\mathrm{SIR}^{(i)}\}. \tag{2.5}$$

The signal power (numerator) and the interference power (denominator) of $\mathrm{SIR}_{worst}$, denoted by $P_s$ and $P_I$, respectively, are also provided to adjacent cells worst SIR estimators in adjacent cells.

### 2.2.3 *Adjacent Cells Worst SIR Estimator*

The adjacent cells worst SIR estimator yields an output, $\mathrm{SIR}^a_{worst}$, which denotes the worst SIR among all adjacent cells with the consideration of the new call's interference influence if the new call request is accepted. The adjacent cells worst SIR estimator obtains $P_s$ and $P_I$ of $\mathrm{SIR}_{worst}$ from the $n$th adjacent cell, denoted by $P_s(n)$ and $P_I(n)$. Then $\mathrm{SIR}^a_{worst}$ can be calculated by,

$$\mathrm{SIR}^a_{worst} = \min_n \left[ \frac{P_s(n)}{P_I(n) + P_t\, G\, D^{-\gamma}(n)\, \Omega} \right], \tag{2.6}$$

where $P_t$ is the transmitted power of the new call, $G$ is the miscellaneous gains of transmission [5], $D(n)$ is the location distance between the new call and the BS of the $n$th adjacent cell, $\gamma$ is the path-loss exponent decided by the terrain [40], and $\Omega$ is the random shadowing component. Note that the $D(n)$ can be obtained by some existing positioning systems such as GPS, and the $P_t\, G\, D^{-\gamma}(n)\, \Omega$ is the amount of the new call's interference effect on the $n$th adjacent cell. Because of the MUD adopted in the WCDMA system, $\mathrm{SIR}^a_{worst}$ is an important parameter in the call admission control. The performance of OFCAC-MUD for WCDMA system with/without considering $\mathrm{SIR}^a_{worst}$ will be shown in section 2.4 Simulation Results.

## 2.3 OFCAC-MUD

The outage-based fuzzy call admission controller (OFCAC-MUD) takes $P_{O,L}$, $P_{O,S}$, $\mathrm{SIR}_{worst}$, and $\mathrm{SIR}^a_{worst}$ as its input linguistic variables. Term sets of fuzzy logic for these input variables are defined as T($P_{O,L}$)={Low (L), Medium (M), High (H)}, T($P_{O,S}$)={Low (L), Medium (M), High (H)}, T(SIR$_{worst}$)={Low (L), Medium (M), High (H)}, and T(SIR$^a_{worst}$)={Low (L), Medium (M), High (H)}. Also, membership functions for terms of linguistic variables use the trapezoid function given by,

$$f(x;x_0,x_1,\alpha,\beta)=\begin{cases}\frac{x-x_0}{\alpha}+1 & ,x_0-\alpha\le x<x_0,\text{when }\alpha>0.\\ 1 & ,x_0\le x\le x_1.\\ \frac{x_1-x}{\beta}+1 & ,x_1<x\le x_1+\beta,\text{when }\beta>0.\\ 0 & ,\text{otherwise.}\end{cases} \tag{2.7}$$

Thus, membership functions for T($P_{O,L}$), T($P_{O,S}$), T(SIR$_{worst}$), and T(SIR$^a_{worst}$) are set, respectively, by,

$$\mu_L(P_{O,L}) = f(P_{O,L};0,a_L P^*_{O,L},0,(a_H-a_L)P^*_{O,L}) \tag{2.8}$$

$$\mu_M(P_{O,L}) = f(P_{O,L};a_H P^*_{O,L},a_H P^*_{O,L},(a_H-a_L)P^*_{O,L},(1-a_H)P^*_{O,L}) \tag{2.9}$$

$$\mu_H(P_{O,L}) = f(P_{O,L};a_H P^*_{O,L},1,(1-a_H)P^*_{O,L},0) \tag{2.10}$$

$$\mu_L(P_{O,S}) = f(P_{O,S};0,b_L P^*_{O,S},0,(b_H-b_L)P^*_{O,S}) \tag{2.11}$$

$$\mu_M(P_{O,S}) = f(P_{O,S};b_H P^*_{O,S},b_H P^*_{O,S},(b_H-b_L)P^*_{O,S},(1-b_H)P^*_{O,S}) \tag{2.12}$$

$$\mu_H(P_{O,S}) = f(P_{O,S};b_H P^*_{O,S},1,(1-b_H)P^*_{O,S},0) \tag{2.13}$$

$$\mu_L(\text{SIR}_{worst}) = f(\text{SIR}_{worst};0,\text{SIR}^*,0,(c_L-1)\text{SIR}^*) \tag{2.14}$$

$$\mu_M(\text{SIR}_{worst}) = f(\text{SIR}_{worst};c_L\text{SIR}^*,c_L\text{SIR}^*,(c_L-1)\text{SIR}^*,(c_H-c_L)\text{SIR}^*) \tag{2.15}$$

$$\mu_H(\text{SIR}_{worst}) = f(\text{SIR}_{worst};c_H\text{SIR}^*,\infty,(c_H-c_L)\text{SIR}^*,0) \tag{2.16}$$

$$\mu_L(\text{SIR}^a_{worst}) = f(\text{SIR}^a_{worst};0,\text{SIR}^*,0,(d_L-1)\text{SIR}^*) \tag{2.17}$$

$$\mu_M(\text{SIR}^a_{worst}) = f(\text{SIR}^a_{worst};d_L\text{SIR}^*,d_L\text{SIR}^*,(d_L-1)\text{SIR}^*,(d_H-d_L)\text{SIR}^*) \tag{2.18}$$

$$\mu_H(\text{SIR}^a_{worst}) = f(\text{SIR}^a_{worst};d_H\text{SIR}^*,\infty,(d_H-d_L)\text{SIR}^*,0). \tag{2.19}$$

The coefficients $a_L$, $a_H$, $b_L$ and $b_H$ are fuzzy set range ratios which are smaller than one. These values affect the ranges of their term sets and should be adjusted to optimize the system utilization. For example, in order to strictly control the average QoS behaviors in the system, the ranges of Low and Medium in $P_{O,L}$ should be made small because $P_{O,L}$ indicates the genuine traffic load situation. On the other hand, $P_{O,S}$ only reflects the instant fluctuation of traffic instead of the average QoS of the system, so the ranges of Low and Medium in $P_{O,S}$ can be set wide. Their thresholds, denoted by $P^*_{O,L}$ and $P^*_{O,S}$, are the system QoS requirements. $P^*_{O,L}$ is usually set to be less than $P^*_{O,S}$ because it is also reasonable to leave a larger space for variation tolerance over a short time interval. Other two linguistic variables, $\text{SIR}_{worst}$ and $\text{SIR}^a_{worst}$, are the current worst SIRs of existing calls in home and adjacent cells. These two variables should not be lower than the threshold $\text{SIR}^*$ given by the system. The coefficients $c_L$, $c_H$, $d_L$ and $d_H$ are the fuzzy set range ratios for $\text{SIR}_{worst}$ and $\text{SIR}^a_{worst}$. These four coefficients are larger than one and also should be adjusted to achieve the best the system utilization.

The output linguistic variable, Z, defined as the acceptability of the new call, has a term set given by T(Z)={Strongly Accepted (SA), Weakly Accepted (WA), Weakly Rejected (WR), Strongly Rejected (SR)}. Table 2.1 shows the fuzzy rule base, which is constructed according to expert domain knowledge. The notation X in this table represents any terms of the linguistic variable. This rule table includes all possibilities of making proper admission decisions. Take rule 10 in Table 2.1 for example. If $P_{O,L}$ is with term Low, $P_{O,S}$ is with term Medium, $\text{SIR}_{worst}$ and $\text{SIR}^a_{worst}$ are with term High, it means the system still has the room for a new call, Z would be with term Strongly Accepted. Also take rule 37 for example. If $\text{SIR}_{worst}$ and $\text{SIR}^a_{worst}$ are with term Low, which means the system should tend to reject the new call, thus Z would be with term Strongly Rejected.

Finally, the fuzzy inference algorithm for the OFCAC-MUD adopts the max-min

Table 2.1: The rule base of the fuzzy call admission controller

| Rule | $P_{O,L}$ | $P_{O,S}$ | $\text{SIR}_{worst}$ | $\text{SIR}^a_{worst}$ | Z | Rule | $P_{O,L}$ | $P_{O,S}$ | $\text{SIR}_{worst}$ | $\text{SIR}^a_{worst}$ | Z |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | L | L | H | H | SA | 23 | L | H | M | M | WR |
| 2 | L | L | H | M | WA | 24 | L | H | M | L | SR |
| 3 | L | L | H | L | WR | 25 | L | H | L | X | SR |
| 4 | L | L | M | H | WA | 26 | M | L | M | H | WA |
| 5 | L | L | M | M | WR | 27 | M | L | M | M | WR |
| 6 | L | L | M | L | SR | 28 | M | L | M | L | SR |
| 7 | L | L | L | H | WR | 29 | M | L | L | H | WR |
| 8 | L | L | L | M | WR | 30 | M | L | L | M | WR |
| 9 | L | M | L | L | SR | 31 | M | L | L | L | SR |
| 10 | L | M | H | H | SA | 32 | M | M | M | H | WA |
| 11 | L | M | H | M | WA | 33 | M | M | M | M | WR |
| 12 | L | M | H | L | WR | 34 | M | M | M | L | SR |
| 13 | L | M | M | H | WA | 35 | M | M | L | H | WR |
| 14 | L | M | M | M | WR | 36 | M | M | L | M | WR |
| 15 | L | M | M | L | SR | 37 | M | M | L | L | SR |
| 16 | L | M | L | H | WR | 38 | M | H | M | H | WR |
| 17 | L | M | L | M | WR | 39 | M | H | M | M | WR |
| 18 | L | M | L | L | SR | 40 | M | H | M | L | SR |
| 19 | L | H | H | H | WA | 41 | M | H | L | X | SR |
| 20 | L | H | H | M | WR | 42 | H | M | M | X | WR |
| 21 | L | H | H | L | WR | 43 | H | M | L | X | SR |
| 22 | L | H | M | H | WA | 44 | H | H | L | X | SR |

inference method [41], and the defuzzification scheme used here is the center of area defuzzification method [39].

## 2.4 Simulation Results

In the simulations, the channel of the WCDMA system suffers inter-cell MAI, intra-cell MAI, AWGN noise, log-normal shadowing [42], and multipath fading; the multipath fading adopts the model of Case 2 in [43]. The path-loss exponent $\gamma$ is 4.35 [40]. The spreading factor of the WCDMA in uplink is 64. The incoming call could be new or handover. The arrival of new calls is modeled as a Poisson with a mean arrival rate, $\lambda$. Two types of traffic are considered - voice and data. The distribution of voice-call holding time is exponential with a mean of 50 seconds. The data packet length is also modelled as an exponential distribution with a mean of 110 bytes. Data call holding time is also exponentially distributed since the transmission rate and spreading factor of each channel are fixed in the simulations. The traffic intensity is defined as $\frac{\lambda}{\mu}$, where $\frac{1}{\mu}$ is the mean call holding time of a voice or a data call. The simulations also consider the soft-handover. A soft-handover user chooses at most 3 BSs in its active set selection. The system adopts selection diversity [5] for the soft-handover. The number of outgoing handover calls in a call duration is also assumed to be 10% proportional to the number of users in a cell. Users are also assumed to be uniformly distributed in cells, and the probabilities of handover to all adjacent cells are equal. Furthermore, the 40% activity factor for a voice call is used [33]. The sampling interval for the outage probability is $5\mu$s, and the sliding window size for long-term (short-term) outage probability is 100K (10K). Three QoS requirements are set to be: $P^*_{O,L} = 10^{-3}$, $P^*_{O,S} = 10^{-2}$, and $\text{SIR}^* = -17$dB.

We consider a 7-cell region as a "cluster" and SIR-based CAC for comparisons. Here the SIR-based CAC is implemented to make admission decision for a new call according to the currently estimated SIR of the system. If the system's SIR is higher than SIR$^*$, then the call will be admitted; otherwise, the call will be rejected. In the implementation, parameters of SIR-based CAC, such as the margin of residual capacity [44] and the margin for handover [45] to tolerate the misjudged admissions, are finely tuned to maximize the system utilization and QoS-guarantee regions. Both perfect power control and no power control situations are investigated. Also, two cases of traffic load distribution: homogeneous case and hotspot case, are investigated. The homogeneous case has all cells given with the same traffic intensity; while the hotspot case has the traffic load in the central cell set to be five times heavier than that in other cells. The following scenarios are observed. In the homogeneous environment, there are (i) OFCAC-MUD without PC, (ii) OFCAC-MUD with perfect PC, (iii) OFCAC using RAKE receiver (OFCAC-RAKE) with perfect PC, (iv) SIR-based CAC using MUD (SIR-based CAC-MUD) without PC, (v) SIR-based CAC-MUD with perfect PC, (vi) SIR-based CAC-RAKE with perfect PC; and in the hotspot environment, there are (vii) OFCAC-MUD without PC, and (viii) SIR-based CAC-MUD without PC.

Figures 2.4(a) and (b) present the maximum long-term and short-term outage probabilities versus the traffic intensity, respectively. The figures reveal that when OFCAC is adopted (scenarios (i), (ii), (iii), and (vii)), the QoS requirements can be always guaranteed. The long-term and short-term outage probabilities of OFCAC grow as the traffic intensity increases, and eventually saturate to $P^*_{O,L}$ and $P^*_{O,S}$ requirements, respectively, in both homogeneous and hotspot environments. On the contrary, when SIR-based CAC is adopted (scenarios (iv), (v), (vi), and (viii)), the QoS requirements are violated. It is because fuzzy logic technology provides a robust mathematical method for admission control in realistic environments [46–48], especially when the mathematical model of the process is too complicated to find. By adopting expert systems to setup the bounded admission rules, the fuzzy approach has the capability to adapt to the dynamic and bursty traffic in multimedia environment to make the best decisions. Another reason is that we use outage probabilities instead of the instant SIR values. When the the system is at heavy load, it is possible to encounter the moments when some users are inactive and thus the instant SIR values are instantly low; then the SIR-based CAC may accept some call requests and the violation of QoS requirements occurs. However, the outage-based CAC can prevent the misjudgment because the outage probability is the average of many SIR values.

Figure 2.5 presents the average number of using channels versus the traffic intensity. It shows that, in homogeneous environment, the maximum capacity of OFCAC-MUD with perfect PC is 225 channels in a cluster, which is about 51% higher than the capacity (about 149 channels) of SIR-based CAC-RAKE with perfect PC before QoS violation (traffic intensity $\leq 0.83$). The improvement is brought by the contributions from SIC MUD and OFCAC. SIC MUD obtains an improvement in capacity by 36.4% as compared to OFCAC-RAKE with perfect PC. The reason is that SIC MUD cancels the home cell's MAI significantly. With perfect PC, OFCAC obtains an improvement in capacity by 5.6% as compared to SIR-based CAC-MUD with perfect PC. Without PC, OFCAC obtains an improvement in capacity by 6.7% as compared to SIR-based CAC-MUD without PC. This is because fuzzy logic techniques have the reasoning capability for resource monitoring and management and takes more aggressive strategies in CAC.

It can also be found that OFCAC-MUD without PC in scenario (i) can accommodate 254 channels in a cluster. The capacity is improved by 12.9% as compared to OFCAC-MUD with perfect PC in scenario (ii). It also has the improvements in capacity by 70.5%, 53.9%, and 19.3% as compared to SIR-based CAC-RAKE with PC (scenario (vi)), OFCAC-RAKE with PC (scenario (iii)), and SIR-based CAC-MUD with PC (scenario (v)), respectively. This indicates that PC may not be suitable in the application of SIC MUD. The reason is that the difference among the users' signals of the received signal for SIC MUD without PC would be more significant than that for SIC MUD with PC. Therefore, SIC MUD without PC can regenerate these MAI signals for cancellation more effectively than SIC MUD with PC. Consequently, few errors are generated in the case without PC. Note that SIC MUD cancels MAI

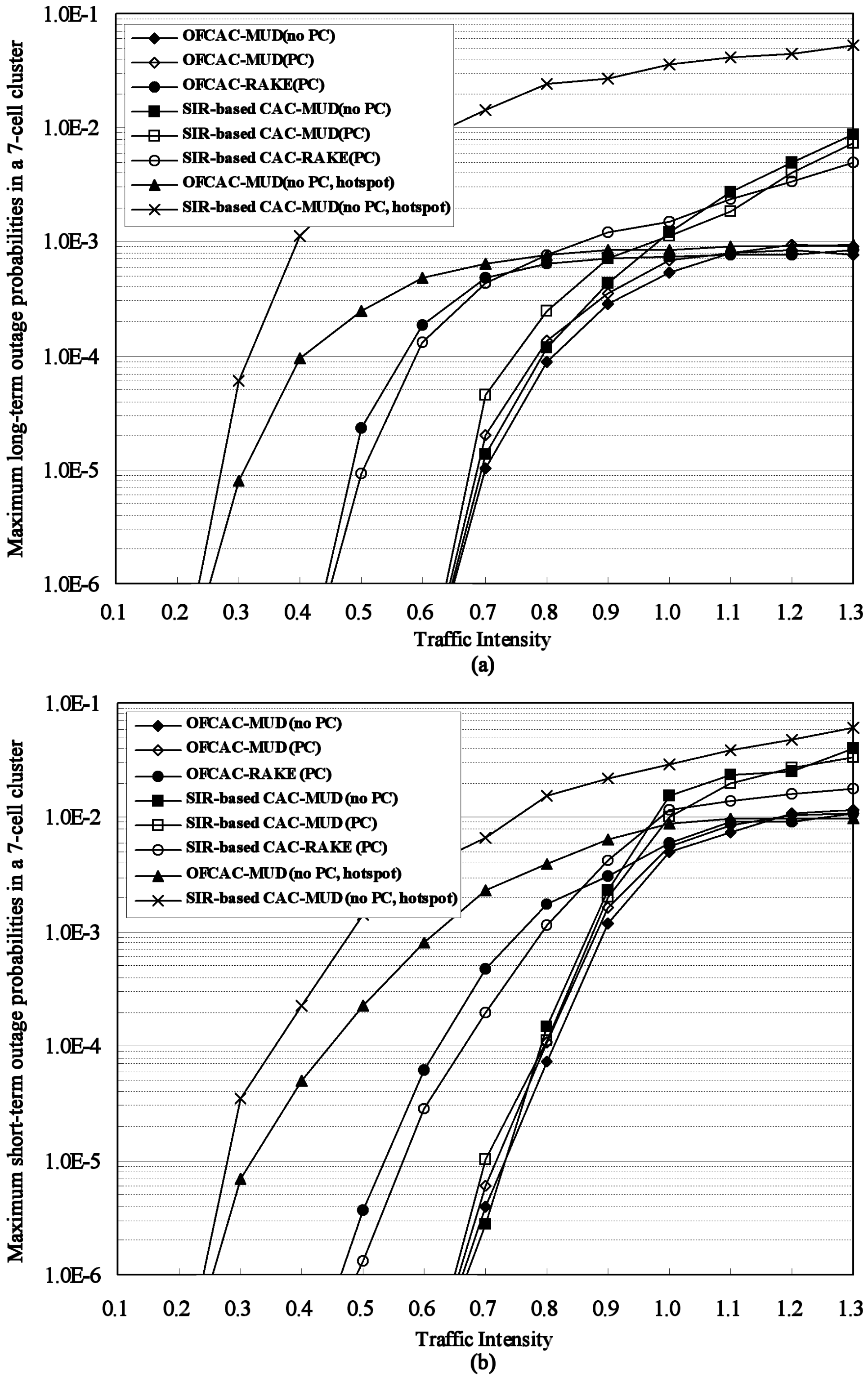


Figure 2.4: (a)Maximum long-term outage probabilities, and (b) Maximum short-term outage probabilities in a 7-cell cluster

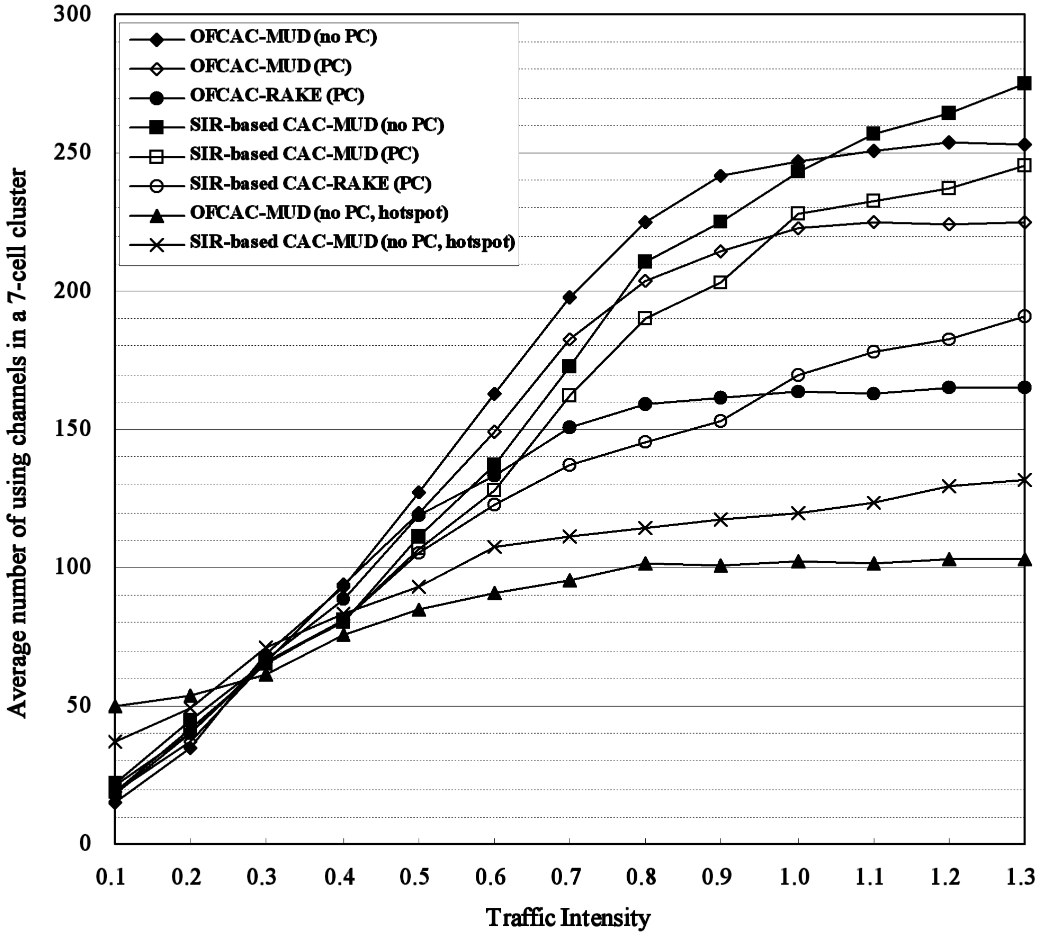


Figure 2.5: The average number of using channels in a 7-cell cluster

of received signal in order.

In the aspect of hotspot environment, the average number of using channels in OFCAC-MUD without PC (scenario (vii)) are much fewer than those of other cases in homogeneous environment. The OFCAC-MUD without PC accommodates 103 channels, while the SIR-based CAC-MUD without PC accommodates 82 channels before QoS violation (traffic intensity $\leq 0.35$). We also simulate the following 2 scenarios: OFCAC-MUD with perfect PC and SIR-based CAC-MUD with perfect PC. Their average numbers of using channels are fewer than those of OFCAC-MUD without PC and SIR-based CAC-MUD without PC, which are quite similar to the phenomena happened in homogeneous environment. The results reveal again that OFCAC-MUD still has better utilization than SIR-based CAC-MUD in the hotspot case. Besides, it means that OFCAC can be applied in the dynamic and bursty traffic environment.

Figures 2.6(a) and (b) present the new call and handover call blocking rates, respectively. Both figures reveal that, when the traffic intensity is smaller than 1.0, OFCAC-MUD without PC has the lowest blocking rates. When the traffic intensity is greater than 1.0, OFCAC-MUD with PC has higher blocking rate than SIR-based CAC-MUD and SIR-based CAC-RAKE because the SIR-based CAC has the risk to violate the QoS requirements and continues to accept call requests.

Figures 2.7(a) and (b) depict the maximum long-term and short-term outage probabilities, respectively, for the WCDMA system with MUD but without considering the adjacent cells worst SIR, $\mathrm{SIR}^a_{worst}$. It is found that the two outage probability requirements are greatly violated for all scenarios under heavy traffic intensity conditions. This verifies the fact, we stated previously, that the adjacent cell SIR plays an essential role in call admission control for WCDMA systems with MUD.

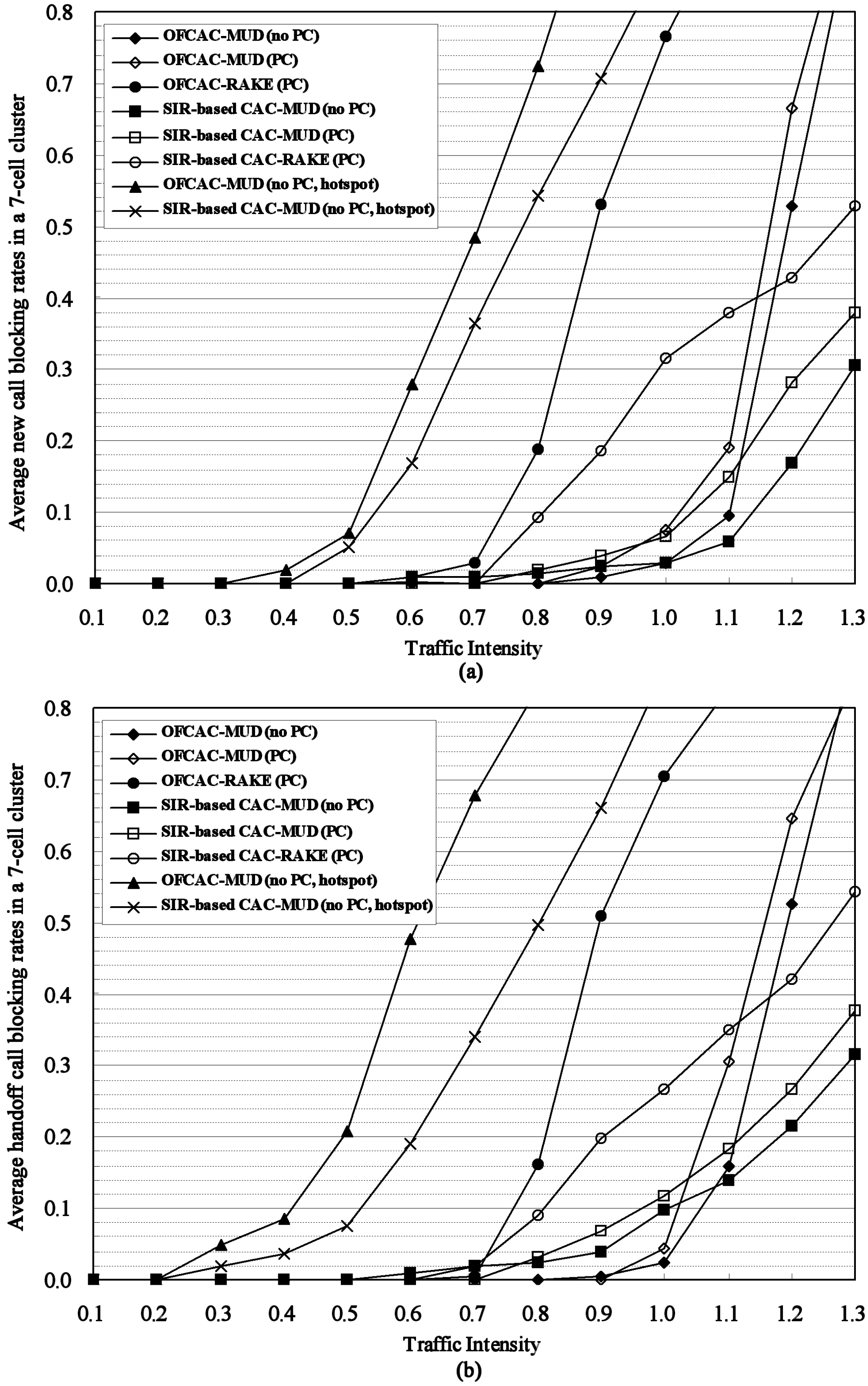


Figure 2.6: (a) Average new call blocking rates, and (b) Average handover call blocking rates in a 7-cell cluster

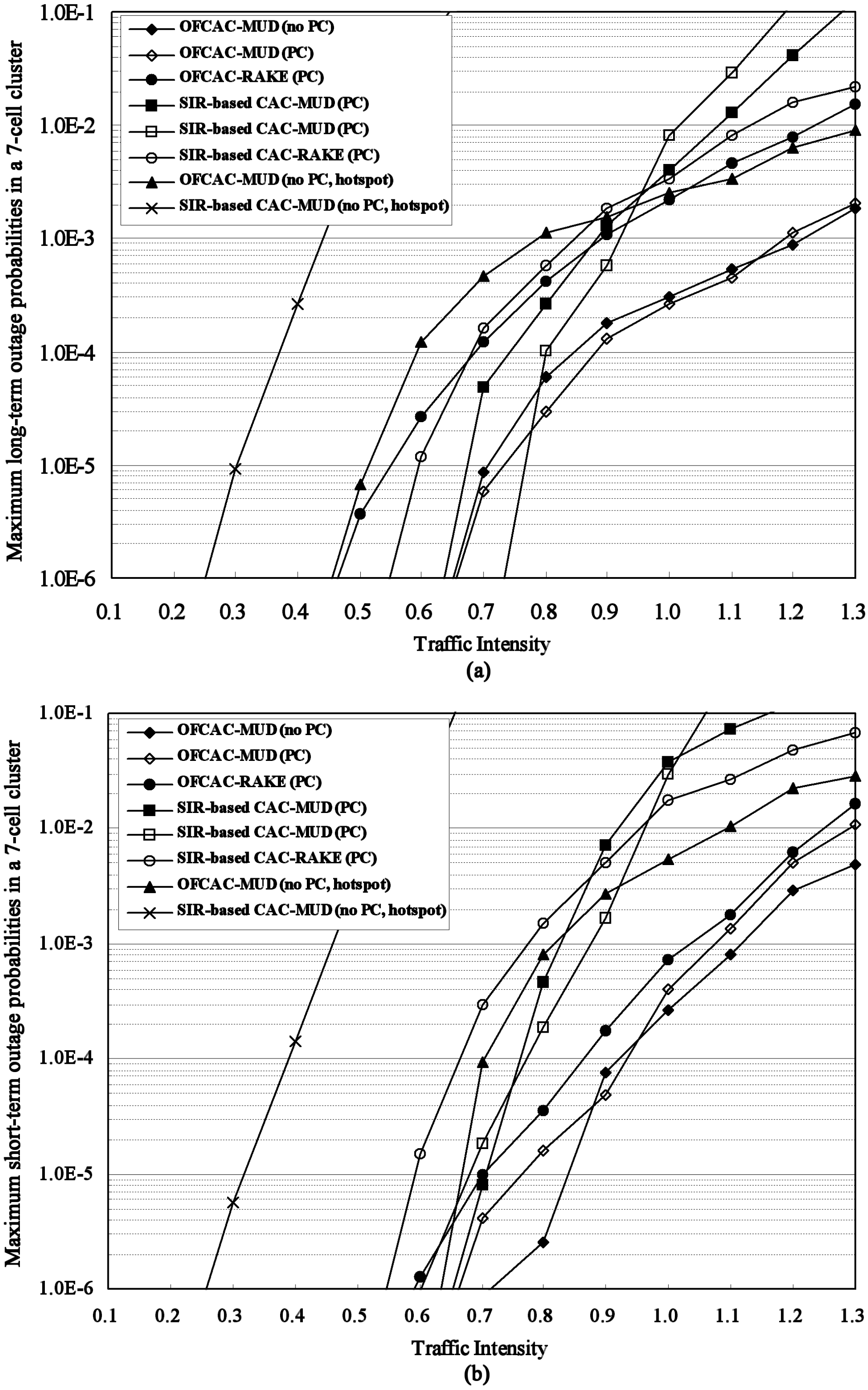


Figure 2.7: (a) Maximum long-term outage probabilities, and (b) Maximum short-term outage probabilities in a 7-cell cluster without considering $\mathrm{SIR}^{a}_{worst}$

## 2.5 Concluding Remarks

This chapter first proposes an outage-based fuzzy call admission controller with multiuser detection (OFCAC-MUD) for WCDMA systems. The OFCAC-MUD considers the short-term outage probability, the long-term outage probability, the home-cell worst SIR, and the adjacent-cell worst SIR including the interference influence of the new call request as the input linguistic variables. The worst SIR of adjacent cells plays an essential role among the input linguistic variables. It is because, when MUD is applied, the inter-cell interference plays a more dominant role than the intra-cell interference in call admission control. Simulation results show that OFCAC-MUD without PC achieves a significant improvement by 70.5% in system capacity as compared to SIR-based CAC-RAKE with PC. Also, OFCAC-MUD without PC can offer more channels for users by an amount of 12.9% than OFCAC-MUD with perfect PC. The reason is that, in the case of perfect PC, the phenomenon of the equal power signals received by SIC MUD will degrade the discrimination of interference of SIC MUD, and then results in the lower cancellation effect. Moreover, OFCAC-MUD can always keep QoS guaranteed, while SIR-based CAC-MUD or SIR-based CAC-RAKE may violate the QoS requirements. Besides, whenever without considering the inter-cell interference in CAC for WCDMA systems with MUD, the QoS violation would occur at heavy traffic intensity even if OFCAC is adopted. This illustrates the essentiality of taking the inter-cell interference into account when making call admission decisions. The OFCAC-MUD, combining the capabilities of the fuzzy logic system and the multiuser detection for call admission control, indeed achieves capacity improvement and QoS guarantee for WCDMA systems.

# Chapter 3

# An Intuitive Scheduling and Admission Controller with Fast Handoff Protocol for Cellular IEEE 802.11e WLAN Systems

## 3.1 Introduction

Wireless local area network (WLAN) is considered to be a good choice of high-speed wireless communication systems to offer a comprehensive multimedia communication platform. It is designed for an alternative access method for Internet applications. The original purpose of WLAN is to reduce the complexity of wiring deployment. Authorized users can access the local network without finding the LAN's receptacles. The high transmission rate and the access flexibility of WLAN make it profitable to provide various services in low-tier coverage. It is known that some real-time services, such as voice over IP (VoIP) and video-stream, are gaining high momentum in WLAN systems. Because of the low cost and easy installation, WLANs are also widely deployed in the public domain. In order to provide broader coverage and continuous network access, the mobile service area of WLANs should be effectively extended, and the cellularized deployment of WLAN systems is one way to achieve this.

The most popular system of WLAN is IEEE 802.11 [2], which provides physical and media access control layer standards for wireless access. In recent years, several enhancements of physical (PHY) and medium access control (MAC) layer in IEEE 802.11 are finished on after the other. The high-speed transmission rate of 802.11 makes many multimedia communications feasible through wireless access. For example, IEEE 802.11b [49] high-rate direct sequence spread spectrum (HR-DSSS) with complementary code keying (CCK) over 2.4GHz ISM band allows 11Mbps maximum transmission rate. IEEE 802.11a [50] and 802.11g [51] specify a higher data rate over U-NII bands and ISM bands, respectively. Both of them adopt orthogonal frequency division multiplexing (OFDM) technology and allows 54Mbps maximum transmission rate. On the other hand, IEEE 802.11 working group also accomplished the amendment for quality of service (QoS). The carry-sense multiple access / collision avoidance (CSMA/CA) procedure in in IEEE 802.11 MAC cannot provide the QoS guarantee. Thus, 802.11 Task Group e (IEEE 802.11e) [52] was established to define QoS parameters and enhanced coordination functions for the transmission opportunities (TXOP) of mobile users.

In order to achieve QoS guarantee in IEEE 802.11e, the call admission controller and TXOP scheduler are essential for the resource management. Several scheduling methods for WLAN have been proposed in [53–57]. QoS or fairness disciplines over MAC are their major considerations. But the MAC layer fulfillment does not mean the actual QoS guarantee because the link quality of air interface between the QoS access point (QAP) and QSTA will affect the error rates and throughput in uplink and downlink.

In this chapter, we first propose an intuitive scheduling and admission control (ISAC) for contention-free services. The ISAC considers the factors of link quality, such as path loss, interference, noise, and QoS requirements,

However, the cellularized WLANs have to face the handoff issue inevitably. the nature of the small coverage of a QoS basic service set (QBSS) in WLANs would lead handoffs of mobile users in the cellular environments. The handoff delay caused by both the scanning time and the medium access time is always a significant index of handoff efficiency. A recent work of IEEE 802.11 Working Group r (IEEE 802.11r) is defining a set of high-efficient frames for associations and authentications to shorten the scanning time [58]. But the medium access time of IEEE 802.11 [2] and 802.11e [52] still needs to be improved. It is because the handoff request (HO-REQ) issued by the handoff QoS station (QSTA) has to compete with other packets in the contention period (CP). The medium access delay is uncertain even if the HO-REQ is assigned as the voice access category (AC_VO), which represents the highest priority in the enhanced distributed channel access (EDCA) [52]. An improved handoff protocol is therefore essential for handoff association in cellular WLAN systems to support inter-cell mobility and seamless services with delay bound guarantee.

In this chapter, we also propose a fast handoff protocol (FHP) for cellular IEEE 802.11e WLAN systems. This FHP devises a *controlled contention period* (CCP), which is partitioned from CP in every beacon interval and designated for HO-REQs. Also, unlike using conventional EDCA in CP, these HO-REQs are arranged to contend sequentially in CCP, and a fuzzy adjustment method (FAM) is proposed to adaptively determine the length of CCP for high system utilization. The FHP, including CCP and FAM, is standard-compatible. It can indeed attain low forced termination rate for HO-REQs and improve system throughput of CP, compared to the conventional EDCA.

The organization of this chapter is as follows. In Section 3.2, the design of ISAC for the cellular IEEE 802.11e WLAN systems is introduced. The system model, media access control, and the design details for ISAC are included in this section. Section 3.3 presents the proposed FHP for cellular IEEE 802.11e WLAN systems. The concepts and details of FHP design are introduced. The simulation results of FHP are also illustrated in this section. Finally, the conclusions are given in Section 3.4.

## 3.2 The Intuitive Scheduling and Admission Controller for IEEE 802.11e WLAN Systems

### 3.2.1 System Model for ISAC

Consider a low mobility IEEE 802.11e cellular WLAN system with HCF mode. Figure 3.1 shows an IEEE 802.11e cellular WLAN environment. The path loss is proportional to the square of distance between transmitter and receiver [5]. The average signal-to-interference-noise ratio (SINR) in downlink (DL) for a $k$th home QoS mobile station (HQSTA($k$)) in its home QoS access point (HQAP) can be given by

$$\mathrm{SINR}_k^D = \frac{\mathcal{P}_{\mathrm{A}}\mathcal{G}/(4\pi d_k)^2}{I_k^D + N_0}, \tag{3.1}$$

where $\mathcal{P}_{\mathrm{A}}$ is the transmitted power from every QAP, $\mathcal{G}$ is the known aggregate devices' gain, $d_k$ stands for the distance between HQSTA($k$) to its HQAP, $N_0$ is AWGN, and $I_k^D$ is the interference measured by HQSTA($k$). It is similar that the average SINR

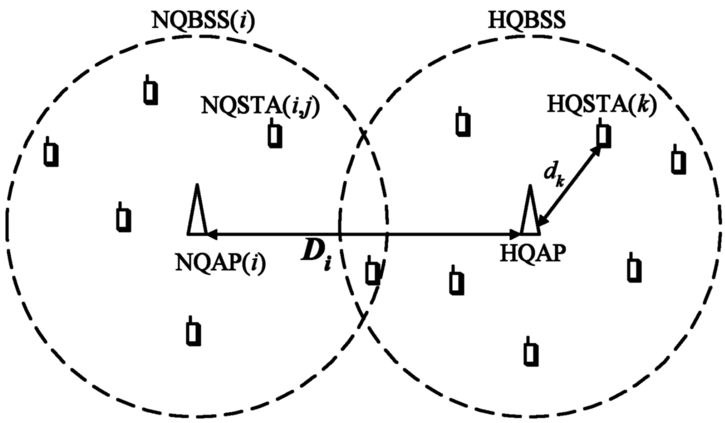


Figure 3.1: IEEE 802.11 WLAN cellular environment

in uplink (UL) at HQAP can be obtained by

$$\mathrm{SINR}_k^U = \frac{\mathcal{P}_{\mathrm{S}}\mathcal{G}/(4\pi d_k)^2}{I_k^U + N_0}, \tag{3.2}$$

where $\mathcal{P}_{\mathrm{S}}$ is the transmitted power of every STA, and $I_k^U$ is the interference measured by HQAP, which consists of the interference from NQAP($i$) and arbitrary NQSTA (NQSTA($i$)) in NQBSS($i$).

The DL bit error probability in HQSTA($k$), denoted as $q_k^D$, can be calculated by $\mathrm{SINR}_k^D$, accordingly. By applying the improved Gaussian approximation method (IGAM) in [59, 60], the DL bit error probability in HQSTA($k$), $q_k^D$, can be approximated as

$$q_k^D = E\left[Q\left(\sqrt{\frac{\mathcal{P}_{\mathrm{A}}\mathcal{G}/(4\pi R d_k)^2}{2Var[\mathcal{P}_{\mathrm{A}}\mathcal{G}]/\mathrm{SINR}_k^D}}\right)\right], \tag{3.3}$$

where $Q[\cdot]$ is the Q-function, $R$ denotes the physical transmission bit rate which is required in the traffic specification (TSPEC) in [52], and $Var[\cdot]$ denotes the variance of the distribution. Thus we can obtain the DL packet error rate by

$$P_{e,k}^D = 1 - (1 - q_k^D)^M, \tag{3.4}$$

where $M$ is the number of bits in a packet. By the similar method, the UL bit error probability from HQSTA($k$) can be approximated as

$$q_k^U = E\left[Q\left(\sqrt{\frac{\mathcal{P}_{\rm S}(k)\mathcal{G}/(4\pi R d_k)^2}{2Var[\mathcal{P}_{\rm S}\mathcal{G}]/{\rm SINR}_k^U}}\right)\right]. \tag{3.5}$$

The UL packet error rate can be expressed by

$$P_{e,k}^U = 1 - (1 - q_k^U)^M. \tag{3.6}$$

### 3.2.2 *Media Access Control in IEEE 802.11e WLANs*

Figure 3.2 depicts the HCF mode in IEEE 802.11e. In the figure, $\mathrm{T_{BI}}$ is the beacon interval (BI) of the system, which can be separated into a duration of beacon, denoted by $\mathrm{T_B}$, and two periods: contention free period (CFP), denoted by $\mathrm{T_{CFP}}$, and contention period (CP), denoted by $\mathrm{T_{CP}}$. $\mathrm{T_E}$ is the time duration of CF-END packet. $\mathrm{T_F}$ is the reserved space for pure contention access in CP. It cannot be ignored because some management frames are transmitted through contention procedure [52]. $\mathrm{TXOP}_i$ contained in $\mathrm{T_{CFP}}$ is the transmission opportunity (TXOP) assigned to the $i$th real-time and QoS-guaranteed link. The concept of the TXOP is the basis to support QoS or real-time services. It represents a polling-based duration for a specific transmission. Therefore a proper scheduling of TXOP for each associated QSTA is essential to provide QoS services.

Let the physical DL and UL transmission rates of a HQSTA be $R^D$ and $R^U$, respectively. And let the required minimum DL and UL data bit rates of the $k$th HQSTA be $\rho_k^D$ and $\rho_k^U$. The minimal required TXOP assigned to the $k$th HQSTA, denoted by $\mathrm{TXOP}_k$, is

$$\mathrm{TXOP}_k = \left(\frac{\rho_k^D}{R^D} + \frac{\rho_k^U}{R^U}\right)\mathrm{T_{BI}} + \mathrm{PIFS} + \mathrm{SIFS}. \tag{3.7}$$

Since HQSTA has to require a minimum transmission rate, the system guarantees the minimal data rates on DL and UL. The TXOP can be regarded as the restrictions

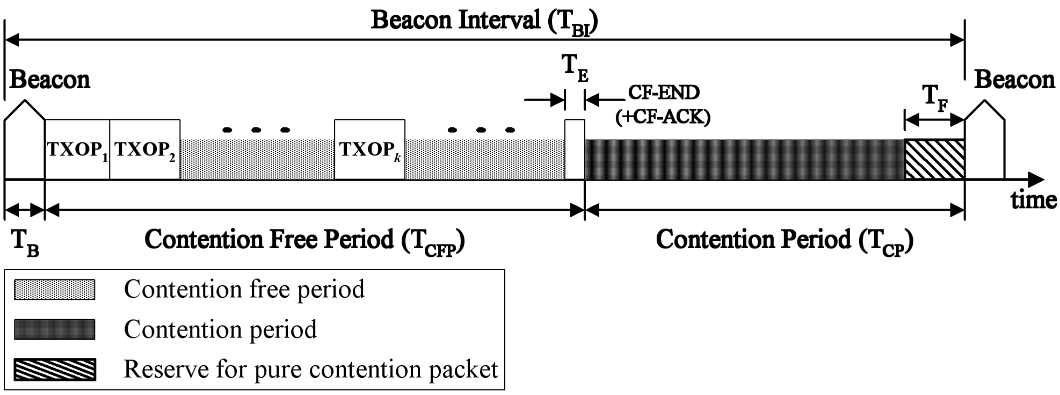


Figure 3.2: HCF mode in IEEE 802.11e

of both UL and DL data transmissions. If the system does not restrict both links, it is possible for the unrestricted one to occupy the resources of other QoS links. According to the principle that the QoS-based services are scheduled into CFP, an intuitive scheduling and admission controller is proposed in the next section.

### 3.2.3 The Design of ISAC

Figure 3.3 depicts the ISAC scheme, which is divided into two phases. When a new HQSTA link request arrives with the required minimum DL and UL data rates, $\rho^D$ and $\rho^U$, the system calculates its $\mathrm{TXOP}_k$ by (3.7) first. Let $\mathrm{T_A} = \mathrm{T_{BI}} - \mathrm{T_B} - \mathrm{T_F}$, which is the current maximum available time for scheduling. In phase 1, the ISAC checks the remaining free time in CFP of the next BI for $\mathrm{TXOP}_k$ of the new HQSTA link request, which uses the following inequality

$$\mathrm{TXOP}_k \leq \mathrm{T_A} - \sum_{i \in S} \mathrm{TXOP}_i - \sum_{j \in \mathcal{N}} \mathrm{TXOP}_j, \qquad (3.8)$$

where $S$ is the set of existing associated HQSTAs in HQBSS, which can be known from the profiles database in HQAP, and $\mathcal{N}$ represents the set of newly accepted HQSTAs at present BI and will start to transmit from next BI. Note that a non-empty $\mathcal{N}$ means more than one new HQSTA request in this BI. All accepted HQSTAs are

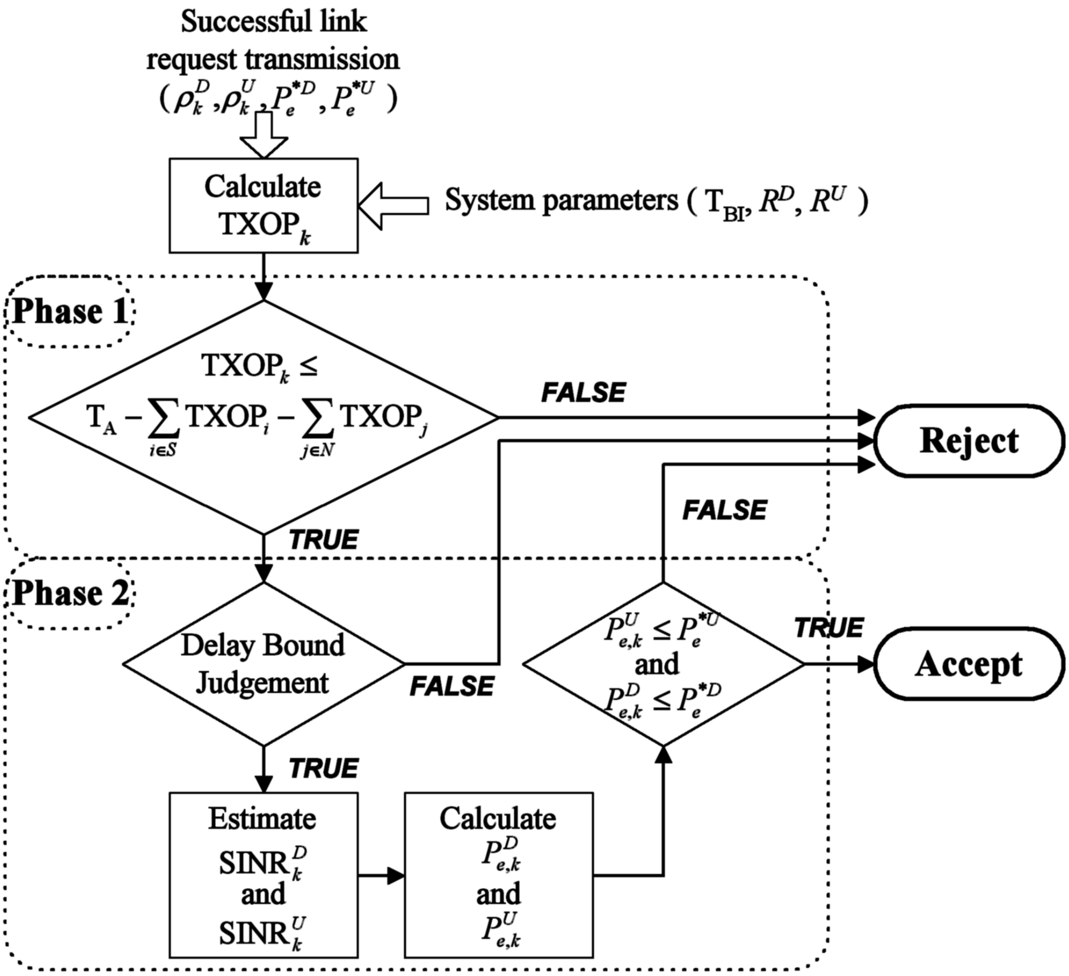


Figure 3.3: ISAC block diagram

treated according to FCFS principle. The inequality (3.8) judges whether there is any space of TXOP for new users by adjusting $T_{CFP}$. If the inequality stands, then the procedure enters phase 2; otherwise the new request will be rejected directly.

In phase 2, the ISAC procedure considers the delay bound and link quality of the new HQSTA, which is decided directly by $T_{BI}$. Assume that the distance between the new HQSTA and HQAP is known. By using (3.1) and (3.2), we can estimate $\text{SINR}_k^D$ and $\text{SINR}_k^U$ of the new HQSTA($k$). Then the packet error rates, $P_{e,k}^D$ and $P_{e,k}^U$, can be obtained by (3.4) and (3.6). Then $P_{e,k}^D$ and $P_{e,k}^U$ are compared to the required thresholds $P_e^{*D}$ and $P_e^{*U}$, respectively. If both UL and DL packet error rates are fulfilled, that is $P_{e,k}^D \leq P_e^{*D}$ and $P_{e,k}^U \leq P_e^{*U}$, then new HQSTA will be accepted. If any one of these two inequalities is violated, which means that the channel quality is too low to allow the new required QoS service, the new HQSTA will be rejected. Note that if $\text{TXOP}_k$ exceeds the maximal allowed value of network allocation vector (NAV) in the system, it can be divided into more than one TXOPs in actual transmissions.

## 3.3 The Design of Fast Handoff Protocol (FHP) in Cellular IEEE 802.11e WLANs

### 3.3.1 System Model for FHP

The cellular WLAN system consists of multiple QBSSs as shown in Fig. 3.4. The QAP QBSS adopts IEEE 802.11a [50] OFDM technology as physical layer specification. The signal quality of the handoff request (HO-REQ) is affected by the channel fading, additive white Gaussian noise (AWGN), and interference. Since WLAN applies unlicensed band, the interference could be co-channel interference and unknown source interference. The co-channel inter-cell interference in the cellular WLAN environments could be reduced by cell-planning, which means that neighboring QBSSs

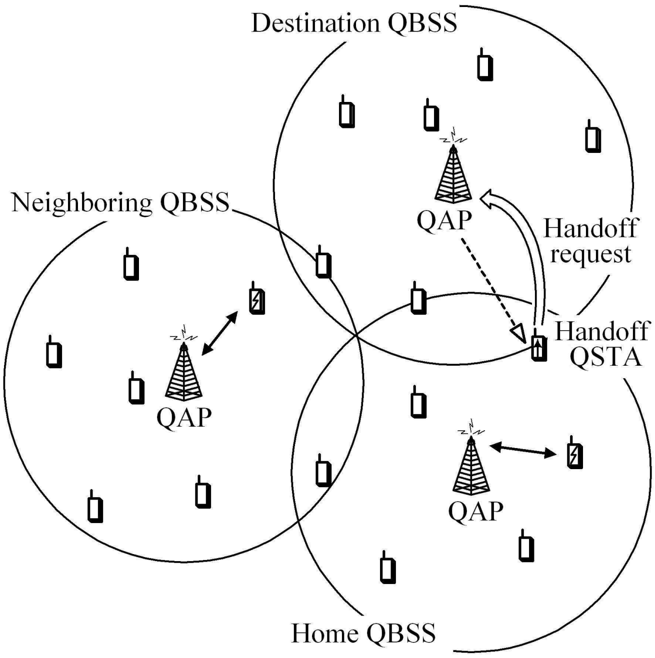


Figure 3.4: Cellular IEEE 802.11 WLAN environment

use different channels. With cell planning, all QAPs can operate asynchronously and do not have to pay extra efforts to synchronize beacons. If it is inevitable for all QAPs to use the same channel, the transmissions of handoff requests must use other unused channels.

In addition, channel fading and AWGN affects the signal of the HO-REQ. Zheng and Miller have analyzed OFDM's performance over Rayleigh fading channels [61]. If the number of OFDM sub-carriers is large enough, the OFDM symbol error probability, denoted by $P_e(\bar{\gamma})$, can be approximated by

$$P_e(\bar{\gamma}) \approx 1 - \exp - \frac{RL}{m(1-R)\bar{\gamma}} \sum_{k=0}^{L-1} \frac{1}{k!} \left( \frac{RL}{m(1-R)\bar{\gamma}} \right)^k , \tag{3.9}$$

where $\bar{\gamma}$ is the average signal-to-interference-noise ratio (SINR), $R$ is the code rate, $L$ is the number of multipaths, and $m$ is 1.24. The average SINRs of DL and UL, denoted by $\bar{\gamma}_D$ and $\bar{\gamma}_U$, respectively, can be estimated by

$$\bar{\gamma}_D = \frac{S_D}{I_D + N_0}, \tag{3.10}$$

and

$$\bar{\gamma}_U = \frac{S_U}{I_U + N_0}, \tag{3.11}$$

where $S_D$ and $S_U$ are received DL and UL signal power; $I_D$ and $I_U$ are measured DL and UL interference; $N_0$ is the power of AWGN. By applying (3.9), both DL and UL symbol error probabilities of OFDM can be obtained.

The fast handoff protocol (FHP) assumes that the QoS access point (QAP) of every QBSS will issue a *handoff controlled access broadcast* (HOCAB) packet in every BI right after the CF-End packet of the CFP and the point coordination function (PCF) interframe space (PIFS). The HOCAB packet is designed to indicate a start of the *controlled contention period* (CCP). Its packet format, shown in Fig. 3.5, is similar to the CF-Poll packet format defined in [52] but with the fields of broadcast destination address (DA) and $N$, where $N$ denotes the number of time slots in CCP. The CCP, partitioned from CP, can be regarded as a kind of controlled access phase (CAP) [52]. As shown in Fig. 3.6, new and failed (retried) HO-REQs will contend for handoff association or authentication in these $N$ time slots. Each slot time equals to the sum of an HO-REQ symbol duration, a short interframe space (SIFS), an acknowledgment (ACK) symbol duration, and a PIFS. As a result, the network allocation vector (NAV) claimed by the CCP can be calculated by multiplying $N$ and the slot time. Also, the time interval between two consecutive HOCABs is called a superframe time. Every new or retried HO-REQ will access for handoff association in the next CCP. Noticeably, the new HO-REQs include those HO-REQs arriving during the previous superframe time, while the retried HO-REQs are the failed HO-REQs

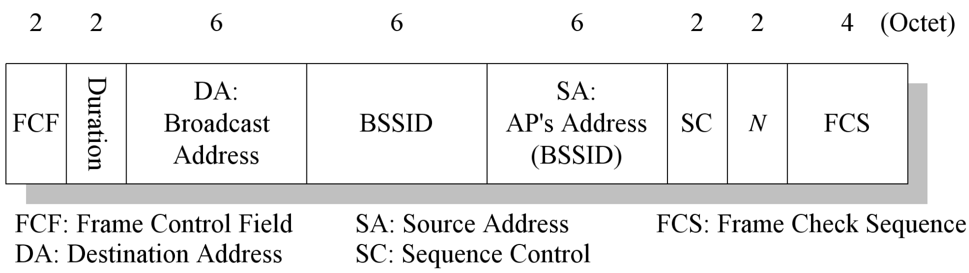


Figure 3.5: The frame structure of the handoff controlled access broadcast (HOCAB) packet

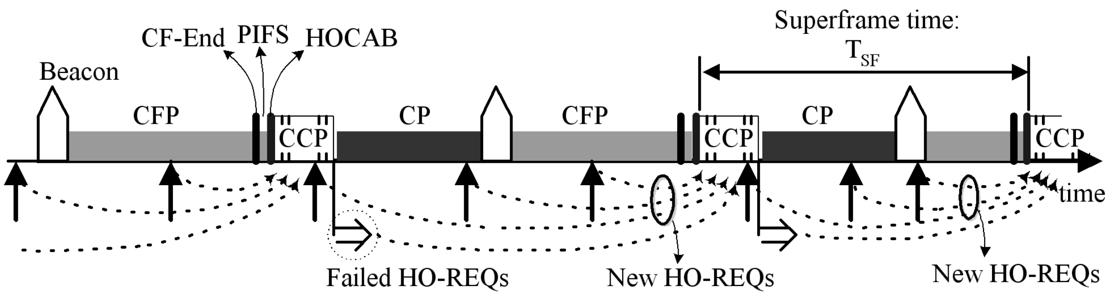


Figure 3.6: The controlled contention period (CCP) in the fast handoff protocol

due to collisions or packet errors in the previous CCP.

### 3.3.2 Performance Analysis of CCP

Figure 3.7 shows the state of the number of handoff requests. We define the $i$th *observed superframe* to be the duration from the HOCAB of the $i$th BI to that of the $(i+1)$th BI. During the $i$th observed superframe, denote the random variable $Nr(i)$ to be the total number of unsuccessful requests in the $i$th CCP, the random variable $A(i)$ to be the number of new arrivals, and the random variable $H(i)$ to be the number of departures, $0 \leq H(i) \leq Nr(i)$. Thus we can obtain

$$Nr(i+1) = (Nr(i) - H(i))^+ + A(i), \tag{3.12}$$

where $(c)^+ = \max(0, c)$. (3.12) means that there are $Nr(i+1)$ requests contending

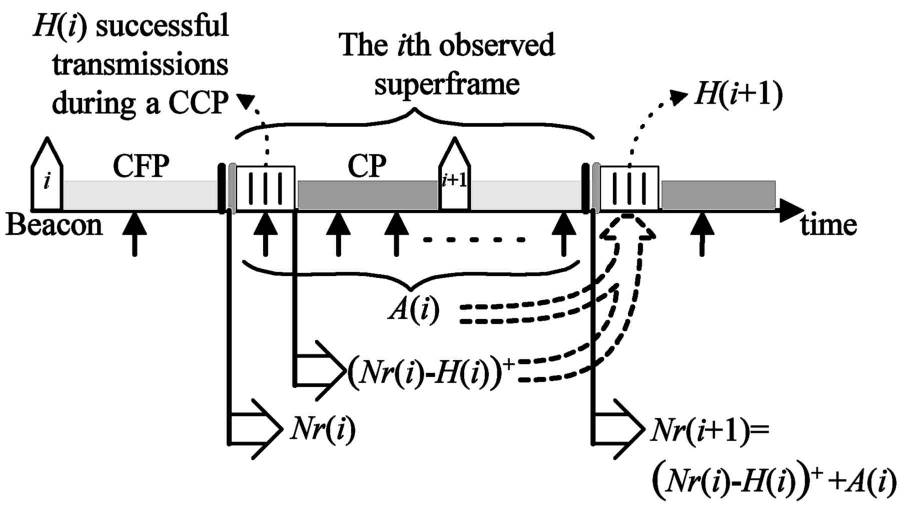


Figure 3.7: The number of HO-REQ arrivals in CCPs

in the $(i+1)$th CCP. Hence, the matrix of transition probabilities given with $H(i) = h$ during the $i$th observed superframe, denoted by $\Phi_h$, can be expressed by

$$\Phi_h = \begin{pmatrix} \alpha_0 & \alpha_1 & \alpha_2 & \alpha_3 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \cdots \\ \alpha_0 & \alpha_1 & \alpha_2 & \alpha_3 & \cdots \\ 0 & \alpha_0 & \alpha_1 & \alpha_2 & \cdots \\ 0 & 0 & \alpha_0 & \alpha_1 & \cdots \\ 0 & 0 & 0 & \alpha_0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \quad \left.\right\} h+1 \text{ rows} \tag{3.13}$$

where $0 \leq h \leq Nr(i)$. Note that $\alpha_x$ is the probability of $x$ arrivals during the $i$th observed superframe. Assume that the arrival process is Poisson with mean arrival rate $\lambda$, hence we can obtain

$$\alpha_x = \Pr\{A(i) = x\} = \frac{e^{-\lambda \mathrm{T}_{\mathrm{SF}}}(\lambda t)^x}{x!}, \tag{3.14}$$

where $\mathrm{T}_{\mathrm{SF}}$ is the duration of the observed superframe. Given $Nr(i) = n$, the limiting probability of $Nr(i)$ conditioned on $H(i) = h$, $i = 0, 1, 2, ...$, can be defined as follows

$$p_{n|H=h} = \Pr(Nr = n|H = h) = \lim_{i\to\infty} \Pr(Nr(i) = n|H(i) = h), \tag{3.15}$$

where $Nr$ and $H$ are the limiting random variables. According to (3.13), (3.15) can be expressed as the following equilibrium equation

$$p_{n|H=h} = \sum_{j=0}^{n} \alpha_j \, p_{n+h-j|H=h} + \alpha_n \sum_{j=0}^{h} p_{j|H=h} - \alpha_n \, p_{h|H=h}, \; n = 0, 1, 2, \ldots . \tag{3.16}$$

Assume that $h$ is given. By using the generating function approach, the $z$-transform of (3.16) can be derived as

$$\begin{aligned}
P_{Nr|H=h}(z) &= \sum_{n=0}^{\infty} \left( \sum_{i=0}^{n} \alpha_i \, p_{n+h-i|H=h} + \alpha_n \sum_{j=0}^{h} p_j - \alpha_n \, p_{h|H=h} \right) z^n \\
&= \sum_{n=0}^{\infty} \sum_{i=0}^{n} \alpha_i \, p_{n+h-i|H=h} \, z^n + \sum_{n=0}^{\infty} \sum_{j=0}^{h-1} \alpha_n \, p_{j|H=h} \, z^n \\
&= z^{-h} \sum_{n=0}^{\infty} \sum_{i=0}^{n} p_{n+h-i|H=h} \, z^{n+h-i} \alpha_i \, z^i + \sum_{j=0}^{h-1} p_{j|H=h} \sum_{n=0}^{\infty} \alpha_n \, z^n \\
&= z^{-h} \sum_{i=0}^{\infty} \alpha_i z^i \sum_{n=i}^{\infty} p_{n+h-i|H=h} \, z^{n+h-i} + P_\alpha(z) \sum_{j=0}^{h-1} p_{j|H=h} \\
&= z^{-h} P_\alpha(z) \left( \sum_{n=h}^{\infty} p_{n+h|H=h} \, z^{n+h} \right) + P_\alpha(z) \sum_{j=0}^{h-1} p_{j|H=h} \\
&= z^{-h} P_\alpha(z) \left( P_{N_r|H=h}(z) - \sum_{j=0}^{h-1} p_{j|H=h} \, z^j \right) + P_\alpha(z) \sum_{j=0}^{h-1} p_{j|H=h} \\
&= z^{-h} P_\alpha(z) P_{N_r|H=h}(z) + P_\alpha(z) \left[ \sum_{j=0}^{h-1} (1 - z^{j-h}) \, p_{j|H=h} \right],
\end{aligned}$$

where

$$P_\alpha(z) = \sum_{n=0}^{\infty} \alpha_n z^n. \tag{3.17}$$

Tnen we can obtain

$$\begin{aligned}
P_{N_r|H=h}(z) &= \frac{P_\alpha(z) \left[ \sum_{j=0}^{h-1} (1 - z^{j-h}) \, p_{j|H=h} \right]}{1 - z^{-h} P_\alpha(z)} \\
&= \frac{P_\alpha(z) \left[ \sum_{j=0}^{h} (z^j - z^h) \, p_{j|H=h} \right]}{P_\alpha(z) - z^h}.
\end{aligned}$$

Then the state probability of (3.18) can be obtained by following equation

$$p_{n|H=h} = \frac{1}{n!} \frac{dP_{N_r|H=h}(z)}{dz^n} \bigg|_{z=1} . \tag{3.18}$$

Moreover, let $\bar{\alpha}$ to be the mean of $\alpha_n$, which can be calculated by

$$\bar{\alpha} = \frac{d}{dz} P_\alpha(z)\Big|_{z=1} = \sum_{n=0}^{\infty} n\alpha_n. \tag{3.19}$$

We also know the fact that $P_{Nr|H=h}(1) = 1$ and $P_\alpha(1) = 1$. By using L'Hôpital's rule, $\bar{\alpha}$ can be expressed as

$$\bar{\alpha} = \frac{d}{dz} P_\alpha(z)\Big|_{z=1}, \tag{3.20}$$

Then (3.18) and (3.17) are applied to obtain

$$\begin{aligned}
1 &= \lim_{z\to 1} P_{Nr|H=h}(z) \\
&= \left.\frac{\frac{d}{dz}\left\{P_\alpha(z)\left[\sum_{j=0}^{h}(z^j - z^h)\, p_{j|H=h}\right]\right\}}{\frac{d}{dz}\left\{P_\alpha(z) - z^h\right\}}\right|_{z=1} \\
&= \left.\frac{\left(\frac{d}{dz}P_\alpha(z)\right)\left(\sum_{j=0}^{h}(z^j - z^h)\, p_{j|H=h}\right) + P_\alpha(z)\left[\sum_{j=1}^{h-1} jp_{j|H=h}\, z^{j-1} - hz^{h-1}\sum_{j=0}^{h} p_{j|H=h}\right]}{\left(\frac{d}{dz}P_\alpha(z)\right) - hz^{h-1}}\right|_{z=1} \\
&= \frac{0 + P_\alpha(1)\left[\sum_{j=1}^{h-1} jp_{j|H=h} - h\sum_{j=0}^{h} p_{j|H=h}\right]}{\left(\frac{d}{dz}P_\alpha(z)\right)_{z=1} - h} \\
&= \frac{\sum_{j=0}^{h}(j-h)\, p_{j|H=h} - hp_{h|H=h}}{\bar{\alpha} - h},
\end{aligned}$$

which implies that

$$\bar{\alpha} = \sum_{j=0}^{h}(j-h)\, p_{j|H=h} + h(1 - p_{h|H=h}). \tag{3.21}$$

The distribution of random variable $H$ would be decided by the contention strategy in CCP. In order to increase the success rate of HO-REQs' access and minimize the forced termination rate of HO-REQs, we will introduce a random strategy with intelligent technique in the following part.

### 3.3.3 A Fuzzy Adjustment Method (FAM)

The contention strategy in CCP assumes that each new and retried HO-REQ will randomly pick an integer to determine which time slot to contend, and the integer is

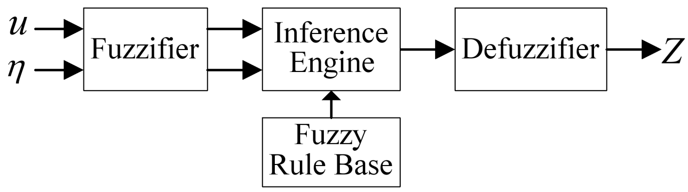


Figure 3.8: The fuzzy logic system for FAM

uniformly distributed over $[1, N]$. In such a way, HO-REQs are guided to sequentially contend so that the collision can be avoided to the utmost. A fuzzy adjustment method (FAM) is also proposed to dynamically adjust $N$ superframe by superframe in order to achieve high system utilization. The block diagram of the fuzzy logic system used for FAM is shown in Fig. 3.8 [39]. Two linguistic variables are chosen as inputs for the FAM. One is the ratio of the number of used slots to $N$ in the previous CCP, which is denoted by $u$; the other is the ratio of successful access power accumulation to the overall access power accumulation in the previous CCP, which is denoted by $\eta$. In order to obtain a more accurate adjustment, a simple transmit power control (TPC) [62] for HO-REQs is applied as a premise. Assume the transmission power of an QAP is known and fixed. Each handoff QSTA can detect the path loss by estimating the power loss of received HOCAB. Therefore the HO-REQ will be transmitted with proper extra power to compensate the path loss. As a result, the power of every HO-REQ received at the QAP would be almost the same.

For the fuzzifier, term sets of fuzzy logic for the two input variables are defined as T($u$)={Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)}, and T($\eta$)={Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)}. Membership functions for the terms of the linguistic variables adopt the trapezoidal function

Table 3.1: Fuzzy Rule Base for FAM

| No. | $u$ | $\eta$ | $Z$ | No. | $u$ | $\eta$ | $Z$ | No. | $u$ | $\eta$ | $Z$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | VL | VL | LD | 10 | L | VH | HD | 19 | H | H | NC |
| 2 | VL | L | MD | 11 | M | VL | LD | 20 | H | VH | LD |
| 3 | VL | M | MD | 12 | M | L | LD | 21 | VH | VL | HI |
| 4 | VL | H | HD | 13 | M | M | LD | 22 | VH | L | HI |
| 5 | VL | VH | HD | 14 | M | H | MD | 23 | VH | M | MI |
| 6 | L | VL | LD | 15 | M | VH | HD | 24 | VH | H | NC |
| 7 | L | L | LD | 16 | H | VL | MI | 25 | VH | VH | NC |
| 8 | L | M | MD | 17 | H | L | LI | | | | |
| 9 | L | H | HD | 18 | H | M | LI | | | | |

given by

$$\mathcal{M}(m; m_1, m_2, m_3, m_4) = \begin{cases} \frac{m-m_1}{m_2-m_1}, & m_1 \le m \le m_2, \\ 1, & m_2 \le m \le m_3, \\ \frac{m_4-m}{m_4-m_3}, & m_3 \le m \le m_4, \\ 0, & \text{otherwise}, \end{cases} \tag{3.22}$$

where $m_1$ and $m_4$ represent two terminals of the lower parallel side, while $m_2$ and $m_3$ represent two terminals of the upper parallel side. Thus, membership functions for term $X$ in T($u$) and term $Y$ in T($\eta$) are expressed, respectively, as

$$\mu_{\text{X}}(u; \mathbf{A}_X) = \mathcal{M}(u; a_{\text{X},1}, a_{\text{X},2}, a_{\text{X},3}, a_{\text{X},4}), \tag{3.23}$$

$$\mu_{\text{Y}}(\eta; \mathbf{B}_Y) = \mathcal{M}(\eta; b_{\text{Y},1}, b_{\text{Y},2}, b_{\text{Y},3}, b_{\text{Y},4}), \tag{3.24}$$

where $\mathbf{A}_X = (a_{\text{X},1}, a_{\text{X},2}, a_{\text{X},3}, a_{\text{X},4})$, and $\mathbf{B}_Y = (b_{\text{Y},1}, b_{\text{Y},2}, b_{\text{Y},3}, b_{\text{Y},4})$, $a_{\text{X},i} \in [0, 1]$, $b_{\text{Y},i} \in [0, 1]$, $i$=1, 2, 3, 4, are 4-tuple elements set ranges for the trapezoidal function $\mathcal{M}$. These ranges should be properly designed to reflect the level of measures in $u$ and $\eta$ so that the FAM could response accurately and precisely when adjusting $N$.

The output linguistic variable, $Z$, defined as the adjustment multiplier of $N$, has a term set given by T($Z$)={High Decrement (HD), Moderate Decrement (MD), Light Decrement (LD), No Change (NC), Light Increment (LI), Moderate Increment (MI), High Increment (HI)}. The term set is a fuzzy singleton, which means that the membership function $\mu_{S \subset \mathrm{T}(Z)}(Z) = 1$ if $Z \in S$ and 0 otherwise. With expert domain knowledge, the fuzzy rule base is designed as listed in Table 3.3.3. Take rule No. 16 in Table 3.3.3 for explanation. If $u$ is with term H but $\eta$ is with term VL, it means that lots of slots in CCP are occupied by the collided HO-REQs, thus $Z$ would be with term MI to relax the congested situation by mildly increasing $N$ in the coming CCP. The inference engine adopts the max-min inference method according the the fuzzy rule base. Also, the defuzzifier adopts the center of area (COA) method to generate output $Z$ [39]. Note that the adjustment result of $N$ will be rounded off to an integer and limited by the minimum of 1.

### 3.3.4 FHP Simulation Results and Discussions

In the simulations, the topology of the cellular IEEE 802.11e WLAN systems contains $7 \times 7$ hexagonal and wrap-around QBSSs . Arbitrary two adjacent QBSSs are assumed to use different physical channels. The radius of coverage of each QAP is 50 meters, and the distance between any two neighboring QAPs is 80 meters. A two-path Rayleigh fading channel model [63] is also considered. The WLAN system and its parameters are based on those in [2, 50, 52], where the SIFS, PIFS, and DIFS are assumed to be 10$\mu$s, 20$\mu$s, and 40$\mu$s, respectively; a beacon interval is 20ms; the duration of CFP is fixed to be 10ms; and a slot time (aSlotTime) of PHY is 9$\mu$s. The slot time in the CCP is given as 78$\mu$s, which is sufficient for a round of an HO-REQ symbol and its ACK.

Two scenarios with different number of contention-based, prioritized static QSTAs, besides the HO-REQs, are assumed in the simulations. In scenario 1 (2), there are 5 (4) QSTAs with background access category (AC_BK), 5 (4) QSTAs with best-effort access category (AC_BE), 1 (2) QSTA(s) with video access category (AC_VI), and 1 (2) QSTA(s) with non-handoff voice access category (AC_VO) [52]. All static QSTAs are located randomly and activated in a saturation mode of that their access transmissions are always activated. The arrival process of the HO-REQ in each QBSS is assumed to be in Poisson distribution. Each HO-REQ has to seek for a successful transmission under the 100ms system delay bound and the 8 times retry limit (dot11LongRetryLimit). Otherwise, the HO-REQ will be forcedly terminated. Noticeably, the delay is the time difference between the HO-REQ arrival and its successful access.

In the aspect of the FAM design, we choose the logarithm function, $\log_{10} k$, $k$=1, 2,..., 10, for the 4-tuple elements of $\mathbf{A}_{\mathrm{X}}$ and $\mathbf{B}_{\mathrm{Y}}$ contained in (3.23) and (3.24), respectively. By such a way, the ranges of trapezoidal functions are wider when measures of $u$ or $\eta$ are lower, and thus FAM would be more sensitive to the worse conditions in $u$ and $\eta$. The trapezoidal fuzzy set ranges of $\mathbf{A}_{\mathrm{X}}$ are set with $\mathbf{A}_{\mathrm{VL}}$=(0, 0, $\log_{10}2$, $\log_{10}3$), $\mathbf{A}_{\mathrm{L}}$=($\log_{10}2$, $\log_{10}3$, $\log_{10}4$, $\log_{10}5$), $\mathbf{A}_{\mathrm{M}}$=($\log_{10}4$, $\log_{10}5$, $\log_{10}6$, $\log_{10}7$), $\mathbf{A}_{\mathrm{H}}$=($\log_{10}6$, $\log_{10}7$, $\log_{10}8$, $\log_{10}9$), and $\mathbf{A}_{\mathrm{VH}}$=($\log_{10}8$, $\log_{10}9$, 1, 1). The same settings are also applied to $\mathbf{B}_{Y}$. The values of $Z$ for the terms HD, MD, LD, NC, LI, MI, and HI are set with 0.25, 0.5, 0.75, 1, 1.25, 1.5, and 2, respectively.

The FHP will be compared with the conventional enhanced distributed channel access (EDCA) method [52], where both HO-REQs and other packets use EDCA to access in CP, but HO-REQs are given with the highest priority (AC_VO).

Fig. 3.9 shows the mean forced termination rate of HO-REQs caused by the overstep of either retry limit (8 times) or system delay bound (100ms). It can be found that the FHP provides an almost zero forced termination rate for HO-REQs, and the performances of FHP are the same in scenarios 1 and 2 . The reasons are that

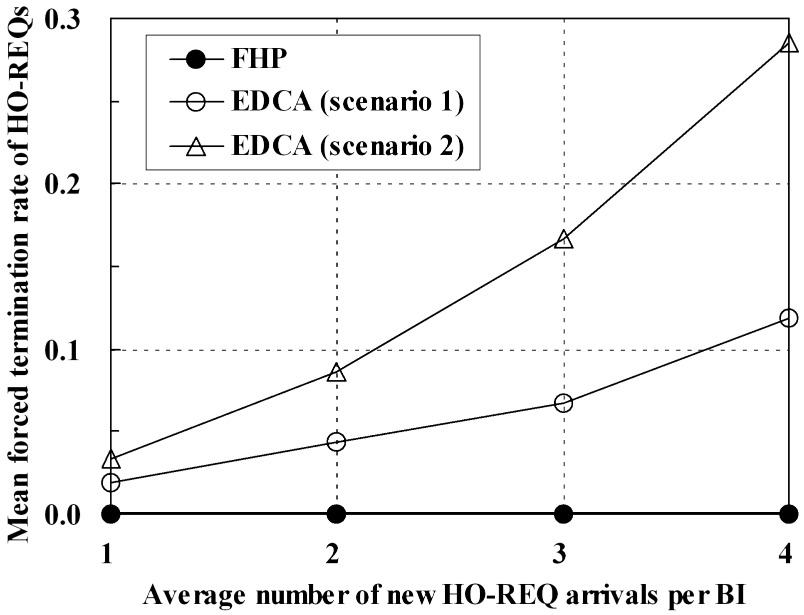


Figure 3.9: Mean forced termination rate of HO-REQs

the FHP designs a CCP dedicatedly designated for HO-REQs and provides a uniform separation for these HO-REQs access, which can prevent HO-REQs from colliding with each other in CCP; also the access of HO-REQs in CCP of FHP are not affected by the contention-based QSTAs in CP. This is a great advantage for the entire handoff process in cellular WLAN systems because the uncertainty of the media access delay of HO-REQs can be eliminated and WLAN systems can obtain more accurate time for other pro-active handoff procedures. The conventional EDCA method, however, attains a large forced termination rate for HO-REQs, which is usually required rather low, say $5\times10^{-3}$ at least. In scenario 1, its forced termination rate is about $1.2\times10^{-2}$ when there is one arrival of the new HO-REQs in average per BI. It further exceeds $6 \times 10^{-2}$ when the average number of new HO-REQ arrivals per BI is higher then 3. Performance in scenario 2 is worse than that in scenario 1. The reasons are that the HO-REQs have to contend with static QSTAs in CP and waste time in backoff, and

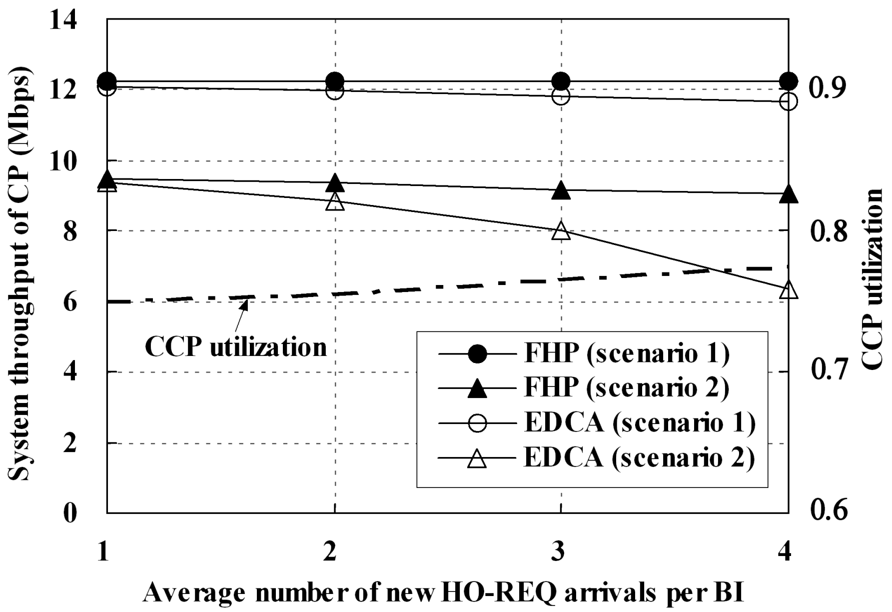


Figure 3.10: System throughput of CP and CCP utilization

the more QSTAs with higher priority such as AC_VI and AC_VO in the system, the worse the forced termination rate of HO-REQs would be.

Fig. 3.10 depicts the system throughput of CP (left vertical axis) and the CCP utilization (right vertical axis), where the system throughput of CP by FHP includes those in CCP and CP, as shown in Fig. 3.6. It can be seen that FHP can still achieve higher system throughput of CP than the conventional EDCA, and the superiority is more significant when the number of high-priority static QSTAs becomes larger (scenario 2). The reason is that FHP designs a dedicated CCP for HO-REQs, which will result in a smaller number of high priority users (only AC_VO) in CP and thus less backoff and collisions for other contention-based packets. The mutual influence between HO-REQs and other contention-based packets can be decreased. Also, FAM provides a high CCP utilization for HO-REQs, which is over 0.75. This implies that there are not too many slots wasted in CCP and the time duration of CCP partitioned from CP is well-controlled by the proposed FAM. Moreover, the system throughput of CP using the conventional EDCA is affected greatly by the number of HO-REQs, and the influence is more deteriorated if more static QSTAs with higher priority exist, as in scenario 2. The phenomenon somewhat justifies the reason we mentioned in this paragraph, which denotes that more high priority QSTAs, including static and handoff, would lead to higher probabilities of backoff and collision in CP.

## 3.4 Concluding Remarks

In this chapter, an intuitive scheduling and admission control (ISAC) scheme is proposed based on IEEE 802.11e cellular WLAN systems. The ISAC scheme considers admission control, based on not only the quality of service (QoS) required by each mobile user, but also the link quality of air interface influenced by fading, noise, and interference. Moreover, a standard-compatible fast handoff protocol (FHP) is proposed for cellular IEEE 802.11e WLAN systems. It consists of a controlled contention period (CCP), which is partitioned from the contention period (CP) for HO-REQs, and a fuzzy adjustment method (FAM) for handoff requests (HO-REQs), which adaptively adjust the proper length of CCP. Simulation results show that the FHP can decrease the forced termination rate of HO-REQs and still enhance the system throughput of CP. This major advantage brought by FHP, which eliminates the uncertainty of media access delay for HO-REQs, is significant. As a result, the WLAN systems can obtain more accurate time estimations for other pro-active procedures in the entire handoff process. This cannot be achieved by using conventional enhanced distributed channel access (EDCA) method in the standards.

# Chapter 4

# A Fuzzy Q-Learning Admission Controller for WCDMA/WLAN Heterogeneous Networks

## 4.1 Introduction

The interworking functionality in a heterogeneous environment has become an essential part for the next generation wireless communication systems. Services in the coming wireless heterogeneous communication systems may have more than one suitable networks and spectrum opportunity to be selected according to the user preference and the air link conditions. The advantage of heterogeneous networks is the complementary flexibility of designs including the coverage, system resource management, and services support. The wireless local area network (WLAN) [2] is suitable for indoor, LAN-based applications because of its high-throughput and small coverage. The cellular system, such as the third generation (3G) WCDMA system, provides better supports in high-mobility, low-latency services but it has lower data rate. Standard bodies of 3G system and WLAN systems are now developing the WCDMA/WLAN interworking standards [4, 64].

Admission control is the first step of system resource management because it directly determines whether the call with multimedia traffic is allowed to enter the system. A lot of researches and approaches of admission control for WCDMA-only or WLAN-only have been proposed to increase the system capacity while maintaining the quality of service (QoS) guarantee. However, these approaches for a single system may not be suitable for heterogeneous systems because they did not consider the other system's situations and *vertical handoff* problems. A user may have more than one options to search for a better spectrum opportunity and utilize one or more links in the heterogeneous networks. Nevertheless, the original QoS has to be maintained when users have to change their access networks.

The vertical handoff with network selection is a good start point for the admission control in the heterogeneous networks. In this case, a new call can be regarded as a virtual handoff call from a 'null' cell. Zhu and McNair [65] used a weighted cost function of each candidate network and formulated the optimization problem with criteria such as requirements of bandwidth, delay, and transmission power. Zhang [66] proposed a vertical handoff decision method by using multiple attribute, which was further solved by the fuzzy logic technique. Chen and Shu [67] proposed an active application oriented mechanism, which made the handoff decision according to a utility function. Song and Jamalipour [68] proposed a grey relational analysis scheme to rank the most suitable destination network in the vertical handoff process. These approaches considered advanced traffic type of multimedia services and formulated the vertical handoff problem as the best decision selection, which outperform traditional signal strength based methods [69]. In addition, the factor of mobility was also considered in the work of Ye et al. [70], which combined the use of position-assisted and mobility perdition for call admission control.

Some recent researches also considered more comprehensive network selection problems in the heterogeneous environment. Maldonado et al. [71] raised the problem to the issue about the cognitive radio, which has a higher flexibility of using the spectrum opportunity and provides a more balanced system loading. Chan et al. [32] proposed a utility-based economic model to solve the resource allocation and network selection problems in heterogeneous networks. Song et al. [72] investigated the WLAN-first call admission scheme for the cellular/WLAN interworking environment, which can achieve the maximum overall resource utilization. Suri and Narahari [73] proposed a novel auction algorithm for procuring wireless channel in heterogeneous networks. All of these works in [32,72,73] also focused on only the decision of a single system for new connections in the heterogeneous networks.

On the other hand, in order to take good advantage of both systems in WCDMA/ WLAN interworking, integrated and efficient mechanisms of admission control for new and handoff calls were proposed to consider overall conditions in such heterogeneous environments. Three measurement-based call admission control (CAC) algorithms in a heterogeneous environment were studied in [74]. Service requirements are compared with measured system resource constrains to decide if the service is admissible. Later, Huang and Ho [75] proposed a straight forward CAC for heterogeneous personal communications service (PCS). Two traffic types, real-time (RT) and non-real-time (NRT), were considered. The higher priority RT traffic and lower priority NRT traffic are compared with predetermined channel occupancy threshold and NRT buffer threshold to determine the admission results. Song and Zhuang [76] proposed an admission control method for voice and data traffic in cellular and WLAN networks with their derived admission regions to select possible service coverages. The policies of admission control considered the different support ability of QoS in cellular and WLAN systems, and some admission strategies are given to maximize the overall system utilization. Niyato and Hossain proposed a cooperative method [77] to consider three systems, IEEE 802.11 WLAN, CDMA cellular wireless access, and IEEE 802.16 WMAN [78], to provide high bandwidth service to the new connection. The estimated result of bandwidth distribution in each network was also referred to the system admission control. But the mobility was not considered and the solution, the *Shaply value* in the core region, was not necessarily optimal under the criteria of system throughput, load-balancing, or utilization. Yu and Krishnamurthy [79] proposed an joint session admission control (JSAC) to optimize the utilization of radio resources in an integrated WLAN and CDMA networks. The QoS of WLAN (throughput and packet delay) and CDMA (signal-to-interference ratio (SIR) outage probability) were used to formulate the admission control problem as a semi-Markov decision process (SMDP). With linear programming method, the admission decision is made based on the QoS state. However, the JSAC does not considered the service types, and the rapid state variation caused by channel changes and user mobility may not reflect in time in such a stochastic-based method.

These mentioned works considered the essential QoS requirements such as data rate, delay bound, packet loss rate, to establish the cost functions for decision making of vertical handoffs. Unfortunately, parameters for the decision were based on either the instant and single channel sounding or the long-term stochastic results. The former could have the risk to make an improper admission decision due to some occasional channel variations, and the later would have the drawback of slower reactions in environment changes. Although the methods with long-term stochastic results can avoid some unnecessary handoffs if the channel states change rapidly, the slower response of the handoff or admission decisions could cause higher forced termination rate and more serious problem with signal deterioration. Therefore in heterogeneous networks, an effective call admission controller should periodically monitor system status such as the number of users, interferences in WCDMA, network busy periods in WLAN, and etc. It also has to be aware of QoS requirements and mobility of users to make the most proper admission decision.

In this paper, we propose *fuzzy Q-learning admission control* (FQAC) for WCDMA/ WLAN heterogeneous networks. The FQAC considers multiple system measures, such as interferences from home cells and other cells, the number of real-time and non-real-time users in the systems as well. It also considers the measures of user mobility and QoS requirements. In order to put all the measures and QoS requirements together for admission decisions, a fuzzy Q-learning (FQL) method [80–82] and a decision maker with minimax theorem [83] are adopted. The FQL integrates the neural-fuzzy inference system (NFIS) [39] with the on-line Q-learning algorithm [80]. Several researches, such as [84] and [85], adopted FQL technology for radio resource management. With the system measures and users' profile, the NFIS will take an action, which is the estimated cost of admission, for each network near the mobile user. Then the decision maker collects the costs and make the final admission/rejection decision by using minimax theorem. The possible actions taken by the NFIS are tuned by the fuzzy Q-learning algorithm, which can simplify the reinforcement learning procedure and increase the feasibility and scalability of real implementation. Without the knowledge of system state transition probability, FQL can iteratively and adaptively adjust the relations between system states and actions by reinforcement learning signals feedbacked from the systems. The complexity of FQAC is low, hence the computation time is very short. It will be a great advantage in reducing the vertical handoff latency. Simulation results show that FQAC performs more aggressive admission decisions than the SIR-based CAC in [44] and the JSAC in [79] when the traffic intensity is low. Hence FQAC has lower new and handoff user blocking rates and higher system utilization while maintaining the QoS. As long as the traffic intensity grows high, FQAC turns to be more conservative, and the blocking rates increase rapidly to avoid QoS violations. Since FQAC has the feature to estimate users mobility intelligently, the admitted (cell) subnetwork is also the one in which the user may dwell longer. This will lower the handoff rate and decrease the handoff blocking rate. Therefore FQAC performs well in fixed, nomadic, and mobile conditions.

The organization of this chapter is as follows. In Section 4.2, the system model for WCDMA/WLAN heterogeneous networks is described. Section 4.3 presents the proposed approach of FQAC. Section 4.4 illustrates simulation results, and finally Section 4.5 draws the conclusions.

## 4.2 System Model

Figure 4.1 shows the WCDMA/WLAN heterogeneous network with FQAC, which is installed in the radio network controller (RNC). Each system is a *subnetwork* of the heterogeneous network. Generally speaking, the subnetwork is deployed with its strategy of topology, these subnetworks could be overlapped with each other.

Denote $\boldsymbol{S}$ a set of all reachable subnetworks of a mobile user. This implies that the pilot or the beacon of the $n$th subnetwork in $\boldsymbol{S}$, denoted by $S_n$ and $S_n \in \boldsymbol{S}$, can be recognized by the mobile user. As a wireless environment considered, a radio signal suffers effects of path loss including attenuation, fading, shadowing, interference, and noise [5, 40, 86]. The most commonly used processes of fading and shadowing are

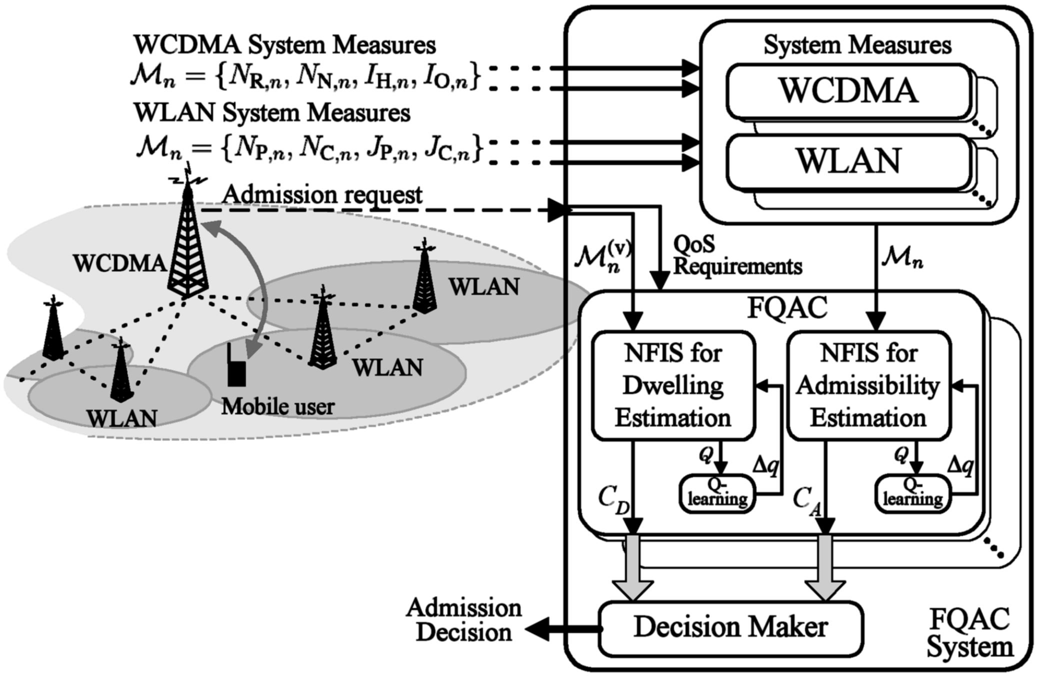


Figure 4.1: The heterogeneous networks and the FQAC system

in Rayleigh and log-normal distribution, respectively, which reflect influences from user's movement and geographical obstacles.

### 4.2.1 WCDMA System Measures

According to the specifications of PHY and MAC in WCDMA systems [87,88], there are a dedicated physical data channel (DPDCH) and a dedicated physical control channel (DPCCH) to carry data and control information, respectively. The admission request of a user is issued to the base station (BS) through a physical random-access channel (PRACH) to ask one DPCCH and none or several DPDCHs. A frame length is 10ms with spreading factor of 256 in DPCCH and 4 to 256 in DPDCH. In WCDMA subnetwork $S_n$, a 4-tuple set of system measures, denoted by $\mathcal{M}_n$, is appropriately chosen as

$$\mathcal{M}_n = \left\{I_{\mathrm{H},n}, I_{\mathrm{O},n}, N_{\mathrm{R},n}, N_{\mathrm{N},n}\right\}, \tag{4.1}$$

where $I_{\mathrm{H},n}$ is home-cell interference, $I_{\mathrm{O},n}$ is other-cell interference, $N_{\mathrm{R},n}$ is the total number of real-time users, and $N_{\mathrm{N},n}$ is the total number of non-real-time users. The first two measures of interference are used to evaluate the remaining capability in the interference-constraint WCDMA system.

### 4.2.2 WLAN System Measures

The major standards of WLAN [2, 50–52] define PHY, MAC, and amendments protocols over 2.4GHz and 5GHz bands. In the chapter, the infrastructure mode is assumed; the beacon interval is set to 20ms, which contains a contention free period (CFP) and a contention period (CP). Usually the CFP is used by real-time users and applies a *polling* method to avoid collision and control delay. The CP is used by non-real-time users and applies carrier sense multiple access/collision avoidance (CSMA/CA) with binary exponential backoff strategy. Since the deployment of the heterogeneous networks is tightly-coupled [4, 26], the admission request of a user for RNC is also through the PRACH to determine to use CFP or CP of the WLAN subnetwork $S_n$. Similarly, in WLAN subnetwork $S_n$, a 4-tuple set of system measures is appropriately selected as

$$\mathcal{M}_n = \left\{ J_{\mathrm{P},n}, J_{\mathrm{C},n}, N_{\mathrm{P},n}, N_{\mathrm{C},n} \right\}, \tag{4.2}$$

where $J_{\mathrm{P},n}$ is the percentages of busy period in CFP per beacon interval (BI), $J_{\mathrm{C},n}$ is the ratio between the period of successful transmission and the busy period in CP per BI, $N_{\mathrm{P},n}$ is total number of users in CFP, and $N_{\mathrm{C},n}$ is the total number of users in CP.

### 4.2.3 The Admission Request

Assume that each mobile user is equipped with WCDMA/WLAN dual modules. The admission request issued by a new or handoff user contains its QoS requirements and mobility measures. Before sending out the admission request, the user should explore the *reachable subnetworks* nearby. A reachable subnetwork is the one that satisfies the constraints of *signal strength* of pilot or beacon. The user detects the signal strength of pilot or beacon around. If the detected pilot or beacon strength of subnetwork $n$, denoted by $\tilde{P}_n$, exceeds a given minimum threshold, the subnetwork is called reachable.

Besides, a mobile user usually has two thresholds to trigger the handoff process [89, 90] in order to prevent the ping-pong effect. When the average received power is lower than the first threshold but higher than the second one, the user will start to explore the reachable subnetworks. If the average received power is lower than the second threshold, the handoff request (with admission request) will be issued.

The QoS requirements in the admission request include minimum data rate ($R^*$), maximum delay ($D^*$), and maximum bit error rate ($\epsilon^*$). The mobility measures in the admission request for $S_n$ are represented by the received pilot/beacon strength, $\tilde{P}_n$, and the detected *Doppler shift*, $\tilde{f}_n$, defined by

$$\tilde{f}_n = \frac{v \cos\theta_n}{\lambda_n}, \tag{4.3}$$

where $v$ is the velocity of the user, $\theta_n$ is the angle between the user's moving direction and the straight line from user to the BS of $S_n$, and $\lambda_n$ is the wavelength of carrier frequency in $S_n$. If $\cos\theta_n$ is positive (negative), the user is approaching (leaving). It can be found that the detected Doppler shift can represent the relative, geographical movement relationship between the user and the BS. This Doppler shift, $\tilde{f}_n$, can be with $\tilde{P}_n$ to estimate the possible dwelling condition of user in $S_n$. Therefore, a 2-tuple set of measures about dwelling condition, denoted by $\mathcal{M}_n^{(\mathrm{v})}$, is selected by

$$\mathcal{M}_n^{(\mathrm{v})} = \{\tilde{f}_n, \tilde{P}_n\}. \tag{4.4}$$

## 4.3 Design of FQAC

The fuzzy Q-learning admission control (FQAC) system, as shown in Fig. 4.1, consists of two neural-fuzzy inference systems (NFISs) for *dwelling estimation* and *admissibility estimation*. The goal of FQAC is to determine the most suitable subnetwork among all reachable subnetworks for a mobile user's call admission request. Every NFIS adopts fuzzy Q-learning method (FQL) [80–82] for its neural network tuning. The FQL can establish an adaptive self-learner and adjust the most proper *actions* (admission costs) taken by NFIS with respect to system *states* including those measures mentioned in (4.1), (4.2), (4.4), and QoS requirements. Its advantage is that the Bellman Optimality in the learning process can be achieved without knowing the state-transition behaviors [80].

### 4.3.1 The Fuzzy Q-Learning (FQL) Method

The block diagram of the fuzzy Q-learning (FQL) method is shown in Fig. 4.2. In the FQL method, there are a set of state vectors, denoted by $\Phi = \{\phi_i, i = 1, 2, ..., M\}$, and a set of actions, denoted by $\boldsymbol{A} = \{A_j, j = 1, 2, ..., N\}$. Also, each fuzzy inference rule is made in the form by

**IF** *input state vector* $\mathbf{x}$ is $\phi_i$, **THEN** *action* is $A_j$ with $q(\phi_i, A_j)$,

where $q(\phi_i, A_j)$ is the Q-value of the state-action pair $(\phi_i, A_j)$, $1 \le i \le M$, $1 \le j \le N$. The policy to select an action for each rule could be *select-max* or other exploration strategies [39,41,91]. To defuzzify the $M$ fuzzy rules, the inferred action for $\mathbf{x}$, denoted

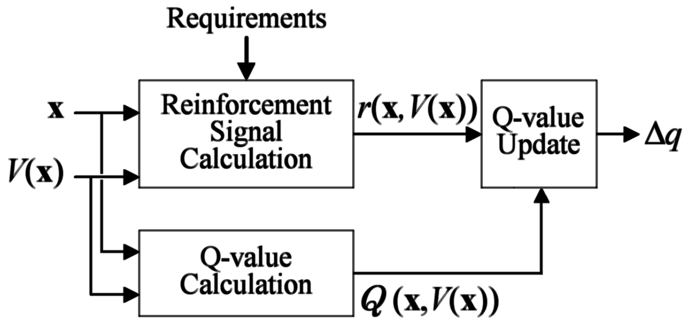


Figure 4.2: The block diagram of the fuzzy Q-learning method

by $V(\mathbf{x})$, is defined as

$$V(\mathbf{x}) = \frac{\sum_{i=1}^{M} w_i A_i}{\sum_{i=1}^{M} w_i}, \tag{4.5}$$

where $w_i$ is the truth value of rule corresponding to $\phi_i$. According to [80], the Q-value of $(\mathbf{x}, V(\mathbf{x}))$, denoted by $Q(\mathbf{x}, V(\mathbf{x}))$, is to reflect the action's fitness with respect to $\mathbf{x}$. The $Q(\mathbf{x}, V(\mathbf{x}))$ is defined by

$$Q(\mathbf{x}, V(\mathbf{x})) = \frac{\sum_{i=1}^{M} w_i \cdot q(\phi_i, A_i)}{\sum_{i=1}^{M} w_i}. \tag{4.6}$$

A reinforcement signal, denoted by $r(\mathbf{x}, V(\mathbf{x}))$, is defined to reflect the difference between the current and the desired results. It is used to adjust the action behaviors in the NFIS when an action is taken. Also the system state will change to a new input state $\hat{\mathbf{x}}$. If the new state-action pair, $(\hat{\mathbf{x}}, V(\hat{\mathbf{x}}))$, is the optimal result, it must satisfy the optimal next-step Q-value defined by

$$Q^*(\hat{\mathbf{x}}, V(\hat{\mathbf{x}})) = \frac{\sum_{i=1}^{M} w_i \cdot q(\phi_i, A_i^*)}{\sum_{i=1}^{M} w_i}, \tag{4.7}$$

where

$$A_i^* = \arg\max_{A_j} \{q(\phi_i, A_j)\}. \tag{4.8}$$

Then the Q-value will be updated by

$$q(\phi_i, A_i) = q(\phi_i, A_i) + \eta \Delta q(\phi_i, A_i), \tag{4.9}$$

where

$$\Delta q(\phi_i, A_i) = \frac{w_i}{\sum_{h=1}^{M} w_h} \cdot \left( r(\mathbf{x}, V(\mathbf{x})) + \gamma Q^*(\hat{\mathbf{x}}, V(\hat{\mathbf{x}})) - Q(\mathbf{x}, V(\mathbf{x})) \right), \tag{4.10}$$

$\eta \in [0,1]$ is the learning rate, and $\gamma \in [0,1]$ is the discount factor used for the reinforcement signal $r(\mathbf{x}, V(\mathbf{x}))$.

### 4.3.2 NFIS for Dwelling Estimation

The NFIS for dwelling estimation is to evaluate the possible dwelling time duration of the user in the subnetwork $S_n$. This NFIS will generate a *dwelling cost* for each $S_n$, denoted by $C_{D,n}$, according to the input state $\mathbf{x}$ designated in $\mathcal{M}_n^{(\mathrm{v})}$ given in (4.4). If the dwelling time duration is longer, the dwelling cost is lower. In the design, an FQL method is applied to implement the NFIS and execute the dwelling estimation. The entities in $\mathcal{M}_n^{(\mathrm{v})}$, Doppler shift $\tilde{f}_n$ and received power $\tilde{P}_n$, are taken as the linguistic variables with the fuzzy term sets defined respectively as $\mathrm{T}(\tilde{f}_n)$={negative high (NH), negative medium (NM), small change (SC), positive medium (PM), positive high (PH)} and $\mathrm{T}(\tilde{P}_n)$={very low (VL), low (L), high (H), very high (VH)}. Accordingly, the dimension of the rule base $M = |\mathrm{T}(\tilde{f}_n)| \times |\mathrm{T}(\tilde{P}_n)| = 20$. The output action is to determine the output linguistic variable, $C_{D,n}$, with the fuzzy term set defined as $\mathrm{T}(C_{D,n})$={very low cost (VLC), low cost(LC), medium cost (MC), high cost (HC), very high cost (VHC)}. Besides, the reinforcement learning signal, $r(\mathbf{x}, V(\mathbf{x}))$, for FQL is defined as

$$r(\mathbf{x}, V(\mathbf{x})) = \left[ \frac{(c\xi - \tau(\mathbf{x}, C_{D,n}))^+}{c\xi} \right]^2, \tag{4.11}$$

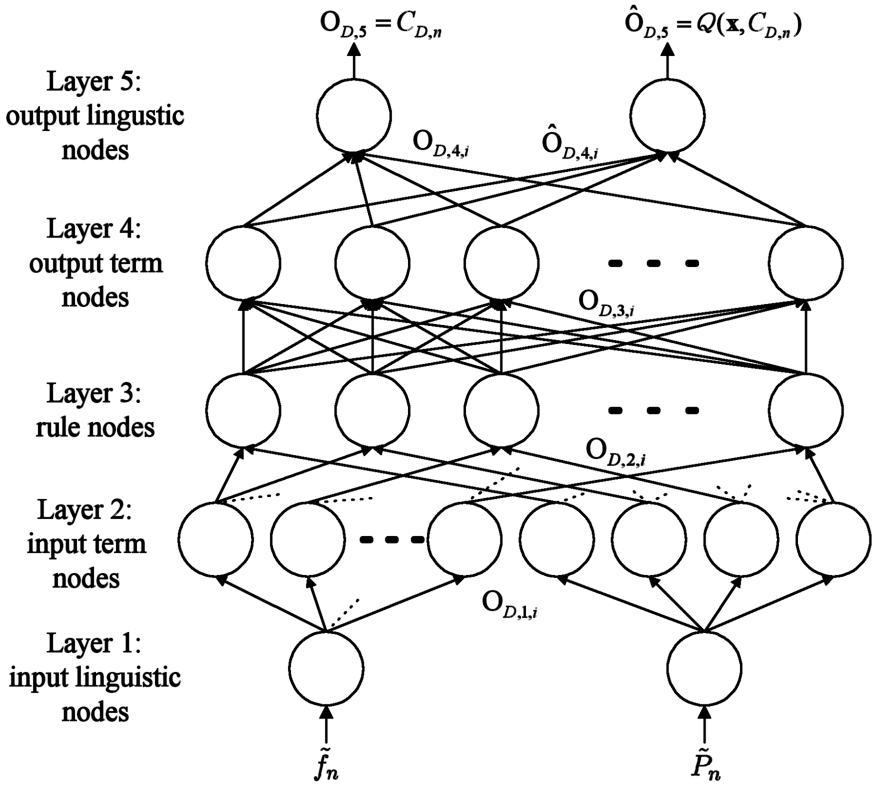


Figure 4.3: A five-layered NFIS for dwelling estimation of subnetwork $S_n$

where $(a)^+$ represents the operation $\max(a, 0)$, $\tau(\mathbf{x}, C_{D,n})$ is the actual average dwell time of users under $(\mathbf{x}, C_{D,n})$ pair, $\xi$ is the maximum handoff delay bound defined by the system, and $c \geq 1$ is a constant. Therefore $c\xi$ is the preferred minimal dwell time for mobile users. This can ensure the mobile user in some $S_n$ to have dwell time long enough to launch next handoff and prevent from too frequent handoffs.

We construct a five-layered NFIS for dwelling estimation of subnetwork $S_n$. As shown in Fig. 4.3, the function of each layer of the NFIS is described as follows.

*Layer 1* is the input layer with two input linguistic nodes. Each input node is a bell-shaper. One input node is for Doppler shift $\tilde{f}_n$, and the other input node is for the received power $\tilde{P}_n$, which are in $\mathcal{M}_n^{(\mathrm{v})}$. There are five (four) identical outputs from $\tilde{f}_n$ ($\tilde{P}_n$) node to the next layer, which are expressed as

$$\mathrm{O}_{D,1,i} = \begin{cases} \exp\left\{\frac{-(\tilde{f}_n-\mu)^2}{2\mu^2}\right\}, & i = 1,2,3,4,5, \\ \exp\left\{\frac{-(\tilde{P}_n-\mu)^2}{2\mu^2}\right\}, & i = 6,7,8,9, \end{cases} \tag{4.12}$$

where $\mu$ is a constant for bias given by every subnetwork.

*Layer 2* is the term node layer with 9 nodes. The left five nodes (nodes 1 to 5) are for term set $\mathrm{T}(\tilde{f}_n)$, and the right four nodes (node 6 to 9) are for term set $\mathrm{T}(\tilde{P}_n)$. Each node $i$, with input $\mathrm{O}_{D,1,i}$, plays the same role as the membership functions in the NFIS. Over this layer, the membership function in node $i$ applies the trapezoid function, which is given by

$$G_i(m) = \begin{cases} \frac{m-m_{i,1}}{m_{i,2}-m_{i,1}}, & m_{i,1} \leq m \leq m_{i,2}, \\ 1, & m_{i,2} \leq m \leq m_{i,3}, \\ \frac{m_{i,4}-m}{m_{i,4}-m_{i,3}}, & m_{i,3} \leq m \leq m_{i,4}, \\ 0, & \text{otherwise}, \end{cases} \tag{4.13}$$

where $m_{Y,1}$ and $m_{Y,4}$ ($m_{Y,2}$ and $m_{Y,3}$) represent two terminals of the lower (upper) parallel sides of the trapezoid. Note that nodes 1 to 5 are for the fuzzy terms in $\mathrm{T}(\tilde{f}_n)$, and node 6 to 9 are for the fuzzy terms in $\mathrm{T}(\tilde{P}_n)$ Thus the output of node $i$ over this layer can be expressed as

$$\mathrm{O}_{D,2,i} = G_i\left(\mathrm{O}_{D,1,i}\right), \quad i = 1,2,...,9. \tag{4.14}$$

*Layer 3* is the rule node layer. This layer implements the truth value of NFIS with fuzzy-AND operator, and node $i$ represents the behavior of rule $i$ with pre-conditioned involvement of node $j$ over *Layer 2*. Since two term sets, $\mathrm{T}(\tilde{f}_n)$ and $\mathrm{T}(\tilde{P}_n)$, are applied, each node over this layer has two inputs. With product operation in each node, the output of node $i$ over this layer can be expressed as

$$\mathrm{O}_{D,3,i} = \prod\{\mathrm{O}_{D,2,j}\}, \quad i = 1,2,...,20. \tag{4.15}$$

*Layer 4* is the output layer. This layer selects the output action in $\mathrm{T}(C_{D,n})$ as the consequence of the $i$th fuzzy rule. Based on the action selection policy and Q-values, the node is to choose an appropriate action out of the possible actions in $\mathrm{T}(C_{D,n})$. In order to obtain a better learning result due to improper initial setting of fuzzy rules, the *semi-uniform distributions* strategy [39, 91] is employed to explore the set of all possible actions. Therefore the node $i$, $i = 1, 2, ..., 20$, over this layer will first select an action $A_i$ for the $(\phi_i, A_i)$ pair with the probability given by

$$P(\phi_i, A_i) = \begin{cases} P^*(\phi_i, A_i^*) + \frac{1-P^*(\phi_i, A_i^*)}{|\mathrm{T}(C_{D,n})|}, & \text{if } A_i = A_i^*, \\ \frac{1-P^*(\phi_i, A_i^*)}{|\mathrm{T}(C_{D,n})|}, & \text{otherwise,} \end{cases} \tag{4.16}$$

where $A_i^*$ can be obtained by (4.8), $P^*(\phi_i, A_i^*)$ is a pre-defined probability that the best action $A_i^*$ is selected, and $|\mathrm{T}(C_{D,n})|$ is the number of terms in $\mathrm{T}(C_{D,n})$. If there are more than one best action, one of them will be selected randomly. The semi-uniform distributions method provides a simple, undirected rule from pure exploration ($P^*(\phi_i, A_i^*) = 0$) to pure exploitation ($P^*(\phi_i, A_i^*) = 1$). Then the node $i$ over this layer will generate two outputs with normalization, which can be expressed by

$$\mathrm{O}_{D,4,i} = \frac{\mathrm{O}_{D,3,i} \times A_i}{\sum_{\ell=1}^{20} \mathrm{O}_{D,3,\ell}}, \tag{4.17}$$

and

$$\hat{\mathrm{O}}_{D,4,i} = \frac{\mathrm{O}_{D,3,i} \times q(\phi_i, A_i)}{\sum_{\ell=1}^{20} \mathrm{O}_{D,3,\ell}}. \tag{4.18}$$

(4.17) and (4.18) are the action-weighted and Q-value-weighted consequence of fuzzy rule $i$ for the next layer.

*Layer 5* decides the dwelling cost of subnetwork $S_n$, $C_{D,n}$, and the Q-value of the state-action vector pair $(\mathbf{x}, V(\mathbf{x}))$, $Q(\mathbf{x}, V(\mathbf{x}))$. They are accomplished by a *center of area* (COA) defuzzification method [39]. The outputs are given by

$$\mathrm{O}_{D,5} = C_{D,n} = \sum_{i=1}^{20} \mathrm{O}_{D,4,i}, \tag{4.19}$$

and

$$\hat{\mathrm{O}}_{D,5} = \sum_{i=1}^{20} \hat{\mathrm{O}}_{D,4,i}. \tag{4.20}$$

Afterward, the reinforcement signal $r(\mathbf{x}, V(\mathbf{x}))$ given by (4.11) can be obtained, and the corresponding Q-value can be updated by (4.9) and (4.10). Moreover, the NFIS for dwelling estimation can be seen as a single-agent learner, Each single sub-network has its own database of the Q-value update and action selection probability for every mobile user. Therefore its learning will converge with rate and precision affected by learning rate $\eta$ and the exploration strategy.

### 4.3.3 NFIS for Admissibility Estimation

The admissibility estimation is designed to guarantee that the admittance of any new or handoff user will not sacrifice the QoS of existing connections. It evaluates the admissibility of the user in the subnetwork $S_n$ with QoS requirements including data rate ($R^*$), delay ($D^*$), and bit error rate ($\epsilon^*$). This functionality will generate an *admissibility cost*, denoted by $C_{A,n}$, in $S_n$ according to the input state $\mathbf{x}$ designated to be $\mathcal{M}_n$ in (4.1) or (4.2). The lower $C_{A,n}$ implies the higher admissibility. Similarly, the FQL method is also used here to implement the admissibility estimation. There four input linguistic variables from $\mathcal{M}_n$. Each linguistic variable, $L_n \in \mathcal{M}_n$, has identical fuzzy term set defined as $\mathrm{T}(L_n)$={very low (VL), low (L), high (H), very high (VH)}. Accordingly, the dimension of the rule base $M = |\mathrm{T}(L_n)|^4 = 256$. The output action is to determine the output linguistic variable, $C_{A,n}$, with the fuzzy term set defined as $\mathrm{T}(C_{A,n})$={strong reject (SRE), reject (RE), fair (FA), accept (AC), strong accept (SAC)}. Besides, the reinforcement learning signal, $r(\mathbf{x}, V(\mathbf{x}))$, for FQL of admissibility estimation is defined as

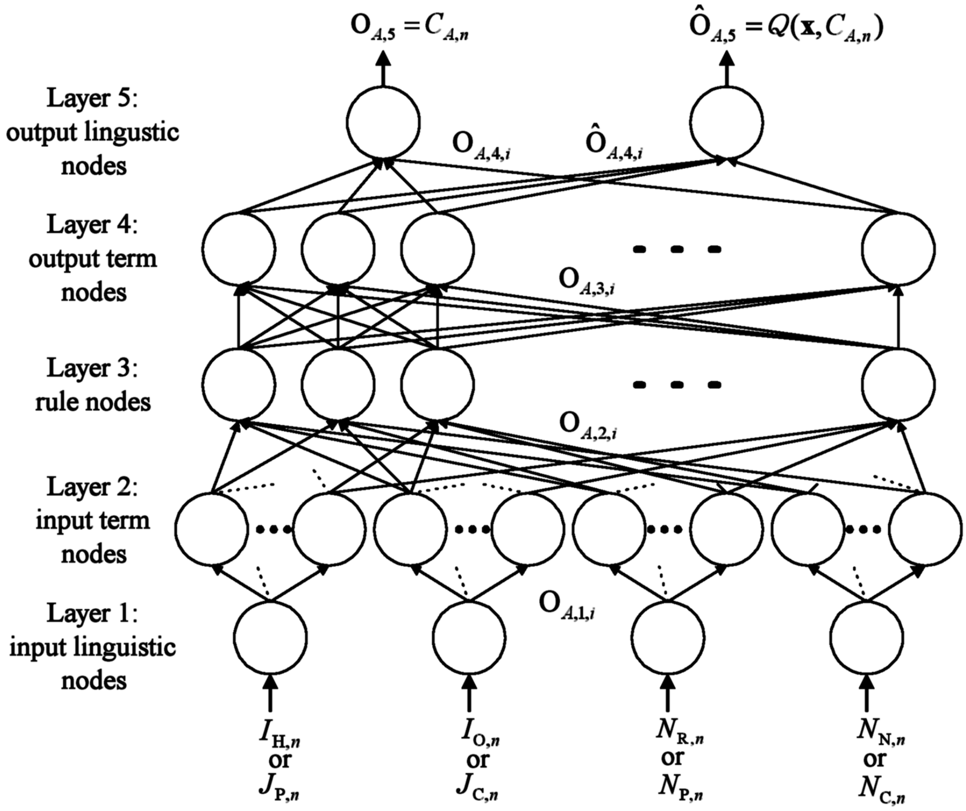


Figure 4.4: A five-layered NFIS for admissibility estimation

$$r(\mathbf{x}, V(\mathbf{x})) = \left[\frac{(R^* - \tilde{R}(\mathbf{x}, C_{A,n}))^+}{R^*}\right]^2 + \left[\frac{(\tilde{D}(\mathbf{x}, C_{A,n}) - D^*)^+}{D^*}\right]^2 + \left[\frac{(\tilde{\epsilon}(\mathbf{x}, C_{A,n}) - \epsilon^*)^+}{\epsilon^*}\right]^2, \tag{4.21}$$

where $\tilde{R}(\mathbf{x}, C_{A,n})$, $\tilde{D}(\mathbf{x}, C_{A,n})$, and $\tilde{\epsilon}(\mathbf{x}, C_{A,n})$ are the resulting QoS with $(\mathbf{x}, C_{A,n})$ pair from system statistics, and $R^*, D^*$, and $\epsilon^*$ are the QoS requirements of the service requested by the mobile user. Also, a five-layered NFIS is constructed for admissibility estimation, as shown in Fig. 4.4. The function of each layer of the NFIS is described as follows.

*Layer 1* is the input layer with two input linguistic nodes. Each of the node applies the same type of bell-shaper in the dwelling estimation for $L_n$ of WCDMA or WLAN systems. Each node has four identity outputs to the next layer. Hence there are total 16 outputs over this layer, which are expressed as

$$\mathrm{O}_{A,1,i} = \exp\left\{\frac{-(L_n-\mu)^2}{2\mu^2}\right\}, \forall L_n \in \mathcal{M}_n, i = 1, 2, ..., 16, \tag{4.22}$$

where $\mu$ is a constant for bias given by every subnetwork. Note that nodes 1 to 4 (5 to 8) (9 to 12) (13 to 16) are for the entity $I_{\mathrm{H},n}$ ($I_{\mathrm{O},n}$) ($N_{\mathrm{R},n}$) ($N_{\mathrm{N},n}$) in WCDMA systems or the entity $J_{\mathrm{P},n}$ ($J_{\mathrm{C},n}$) ($N_{\mathrm{P},n}$) ($N_{\mathrm{C},n}$) in WLAN systems.

*Layer 2* is the term node layer with 16 nodes for $\mathrm{T}(L_n)$, as shown in Fig. 4.4. The trapezoid function in (4.13) is also adopted as the membership functions over this layer. The output of node $i$ can be expressed as

$$\mathrm{O}_{A,2,i} = G_i\left(\mathrm{O}_{A,1,i}\right), \quad i = 1, 2, ..., 16. \tag{4.23}$$

*Layer 3* is the rule node layer with fuzzy-AND operator. Since the FIS for admissibility estimation has four input linguistic variables, each node over this layer has four inputs. With product operation, the output of node $i$, $i = 1, 2, ..., 256$, over this layer can be expressed as

$$\mathrm{O}_{A,3,i} = \prod\{\mathrm{O}_{A,2,j}\}, \tag{4.24}$$

where $j$ is the node index over layer 2 that is used in the $i$th rule.

*Layer 4* is the output layer, which selects the output action in $\mathrm{T}(C_{A,n})$ as the consequence of the $i$th fuzzy rule. Each node over this layer will choose an appropriate action from $\mathrm{T}(C_{A,n})$ based on the action selection policy and Q-values. Similarly, the semi-uniform distributions is also employed as the exploration strategy. Therefore the node $i$, $i = 1, 2, ..., 256$ over this layer will first select an action $A_i$ for the $(\phi_i, A_i)$ pair with the probability given by

$$P(\phi_i, A_i) = \begin{cases} P^*(\phi_i, A_i^*) + \frac{1-P^*(\phi_i,A_i^*)}{|\mathrm{T}(C_{A,n})|}, & \text{if } A_i = A_i^*, \\ \frac{1-P^*(\phi_i,A_i^*)}{|\mathrm{T}(C_{A,n})|}, & \text{otherwise,} \end{cases} \tag{4.25}$$

where $A_i^*$ can be obtained by (4.8), $P^*(\phi_i, A_i^*)$ is a pre-defined probability that the best action $A_i^*$ is selected, and $|\mathrm{T}(C_{A,n})|$ is the number of terms in $\mathrm{T}(C_{A,n})$. If there are more than one best action, one of them will be selected randomly.

Then the node $i$ over this layer will generate two outputs with normalization, which can be expressed by

$$\mathrm{O}_{A,4,i} = \frac{\mathrm{O}_{A,3,i} \times A_i}{\sum_{\ell=1}^{256} \mathrm{O}_{A,3,\ell}}, \tag{4.26}$$

and

$$\hat{\mathrm{O}}_{A,4,i} = \frac{\mathrm{O}_{A,3,i} \times q(\phi_i, A_i)}{\sum_{\ell=1}^{256} \mathrm{O}_{A,3,\ell}}. \tag{4.27}$$

(4.26) and (4.27) are the action-weighted and Q-value-weighted consequence of fuzzy rule $i$ for the next layer.

*Layer 5* decides admissibility cost of $S_n$, $C_{A,n}$, and the Q-value of the state-action vector pair $(\mathbf{x}, V(\mathbf{x}))$, $Q(\mathbf{x}, V(\mathbf{x}))$, by COA defuzzification method, too. The outputs are given by

$$\mathrm{O}_{A,5} = C_{A,n} = \sum_{i=1}^{256} \mathrm{O}_{A,4,i}, \tag{4.28}$$

and

$$\hat{\mathrm{O}}_{A,5} = \sum_{i=1}^{256} \hat{\mathrm{O}}_{A,4,i}. \tag{4.29}$$

With the reinforcement signal in (4.21), the learning update for action selection in the NFIS can be calculated by (4.9) and (4.10). In the design, each single subnetwork has its own database of the Q-value update and action selection probability for every type of service. The convergence performance of Q-learning is affected by the learning rate $\eta$ and the exploration strategy in (4.25).

### 4.3.4 The Decision Maker

The decision maker in the FQAC system determines the admission result based on a *minimax* theorem [83], which is an optimal approach for mixed strategies in statistical decision theory and zero-sum game theory proved by Jonas von Neumann in 1928. The simplest example of minimax theorem is the game of sharing a piece of cake between two persons. The game is restricted by two rules. Rule one is that one person can cut a piece of cake in any way or shape, and rule two is that the other one has the priority to choose. Therefore the best strategy for the first one is to cut the cake in half, which is the identical result when applying the minimax theorem. There are some well-known applications of minimax theorem. For example, it is used to solve the *Mountain Pass Theorem* (MPT), indicated by Ambrosetti and Rabinowitz in 1973, to find the critical point, usually the *saddle point*, of the sequence [83]. Another common application is to decide the best moving strategy in the two or multiple players game with the alternate moving rule.

The examples mentioned above imply that minimax theorem provides a best decision rule for zero-sum multiple players game. In the admission decision, the selected subnetwork have to be responsible for ALL required resources of the mobile user, so it can be regarded as a zero-sum game. According to the minimax theorem, the expected maximum impact, which is represented by the dwelling and admissibility costs, can be minimized. The chosen subnetwork $m$ for the new or handoff user has to satisfy

$$m^* = \arg\min_m \{\max \{C_{D,m}, C_{A,m}\} \ \ |\forall m\} . \tag{4.30}$$

If there are multiple results in $m$, then an arbitrary one will be selected. If the reachable subnetwork does not exist, or the result cost of the chosen subnetwork $m$

is equal to one, it implies that the subnetwork cannot support the required QoS or mobility. Therefore FQAC will reject the user's admission request.

The ultimately chosen subnetwork is that with the minimal cost among all possible maximal costs. The decision will lead the FQAC to behave more aggressive when the overall load is light, and more conservative when the overall load is becoming heavy to ensure QoS guarantee.

## 4.4 Simulation Results

### 4.4.1 Simulation Environment

We consider a WCDMA system containing $7 \times 7$ hexagonal and wrap-around WCDMA cells for simulations. The longest distance between the BS and the cell boundary is one kilometer. The channel of the WCDMA system suffers inter-cell MAI, intra-cell MAI, AWGN noise, log-normal shadowing [42], and multipath fading [43]. The path-loss exponent is 4.35 [40]. The spreading factor is from 4 to 128. Perfect power control is used in the system.

The arrival of new calls in each cell is modeled as a Poisson process with a mean arrival rate $\lambda$. Four types of traffic are considered: real-time voice, real-time video, non-real-time data, and non-real-time best effort. The traffic intensity is defined as the product of mean arrival rate and mean session time of a service type. Users are also assumed to be uniformly distributed in cells, and a random-walk model is used to simulate the mobility of every user. Similarly, all mobile users in WLAN are located randomly and activated in a saturation mode of that their access transmissions are always on. The new user arrival process is assumed to be in Poisson distribution. There are four types of traffic: real-time voice, real-time video stream, non-real-time

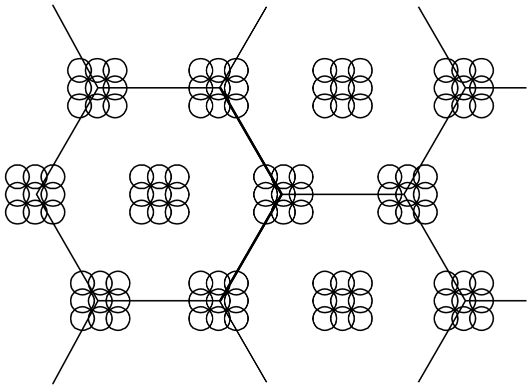

Figure 4.5: The topology of WCDMA/WLAN subnetworks for simulations

data, and best-effort. Their QoS requirements are listed in Table 4.1. Since the requirements can be supported in both WCDMA and WLAN systems, there would be no data rate problem to handoff vertically from WLAN (higher bandwidth) to WCDMA (lower bandwidth).

As shown in Fig. 4.5, the WLAN subnetworks are fully overlapped over the WCDMA networks. A WLAN subnetwork group consists of $3\times 3$ round QoS basic service sets (QBSSs). The centers of WLAN subnetwork groups are located at the same place of WCDMA's BSs and the cross-point of 3 WCDMA cells' boundaries. The radius of each QBSS is 100 meters, and any two adjacent QBSSs are assumed to use different channel frequencies. Both Rayleigh and log-normal fading channel models are also considered. The WLAN system parameters are based on those in [50, 52], where the SIFS, PIFS, and DIFS are assumed to be 10$\mu$s, 20$\mu$s, and 40$\mu$s, respectively; a beacon interval is 20ms; the maximum duration of CFP is 15ms; and a slot time (aSlotTime) of PHY is 9$\mu$s. The value of $\xi$ and constant $c$ in (4.11) are 500ms and 3, respectively. The bias constant $\mu$ in (4.12) and (4.22) are 0. In order to eliminate the handoff latency of the handoff request contention in the WLAN system, the *Fast*

Table 4.1: QoS Requirements

| Traffic type | Min. data rate (kbps) | Delay bound (ms) | BER |
|---|---|---|---|
| Voice | 32 | 100 | $10^{-3}$ |
| Video stream | 64 | 100 | $10^{-3}$ |
| Data | 128 | 1,000 | $10^{-6}$ |
| Best-effort | 1 | 10,000 | $10^{-5}$ |

*Handoff Protocol* [92] is adopted to provide efficient inter-AP transitions.

The FQAC will be compared to conventional SIR-based call admission control (CAC) [44] and joint session admission control (JSAC) [79]. The SIR-based CAC is implemented to make admission decision for a new user according to the currently estimated SIR of the system. If the system's SIR is higher than the threshold SIR$^*$, then the call will be admitted; otherwise, the call will be rejected. In the implementation parameters of SIR-based CAC, such as the margin of residual capacity [44] and the margin for handoff [45] to tolerate the misjudged admissions, are finely tuned according to the greedy approach in [93] to maximize the system utilization and handoff failure constrains. As to JSAC, a brief description is given in Section 4.1.

### 4.4.2 Simulation Results

Fig. 4.6 depicts the QoS guarantee ratio for all services versus the average traffic intensity. It can be found that FQAC can maintain almost all users' QoS. When the traffic intensity is as high as 1.5, the QoS guarantee ratio is still over 98%. The JSAC, however, has a few QoS violations over high traffic intensity, and has apparent degradation performance when the traffic intensity comes to very high. Also, the SIR-based CAC get the worst guarantee region. It is because the SIR-based CAC has only instant channel soundings for admission decisions. It could be affected by temporary channel fluctuations, cause misjudgment of system situation, and eventually lead

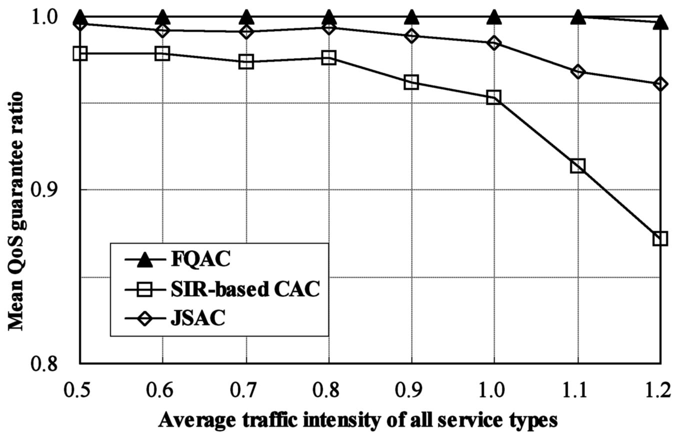


Figure 4.6: QoS guarantee ratio

abnormal low blocking rate and overload the system capacity.

Figure 4.7 depicts the average blocking rates of new mobile users for four types of service versus the average traffic intensity. It can be found that the FQAC can keep the blocking rate until the traffic intensity becomes extremely high. Because admitting a real-time service has higher impact than accepting a non-real-time service, the blocking rate of a real-time request is higher than that of a non-real-time request. This will ensure to achieve QoS guarantee of all existing users. The reason of such performance is that the FQAC consider more realistic and essential measures of both WCDMA and WLAN systems. The system states can be really reflected in the admission results. The JSAC method also has the same property, but the blocking rate is a little bit higher. The reason is that JSAC has to mitigate the influence of user mobility, so it sacrifices the system utilization. The blocking rate of SIR-based CAC is the lowest when the traffic intensity is high. It is because the CAC is decided according to a short period of SIR measurement, which is possible to obtain a temporary low value of the signal fluctuation, and would accepted too many users.

Fig. 4.8 shows the average handoff user blocking rates for four types of service

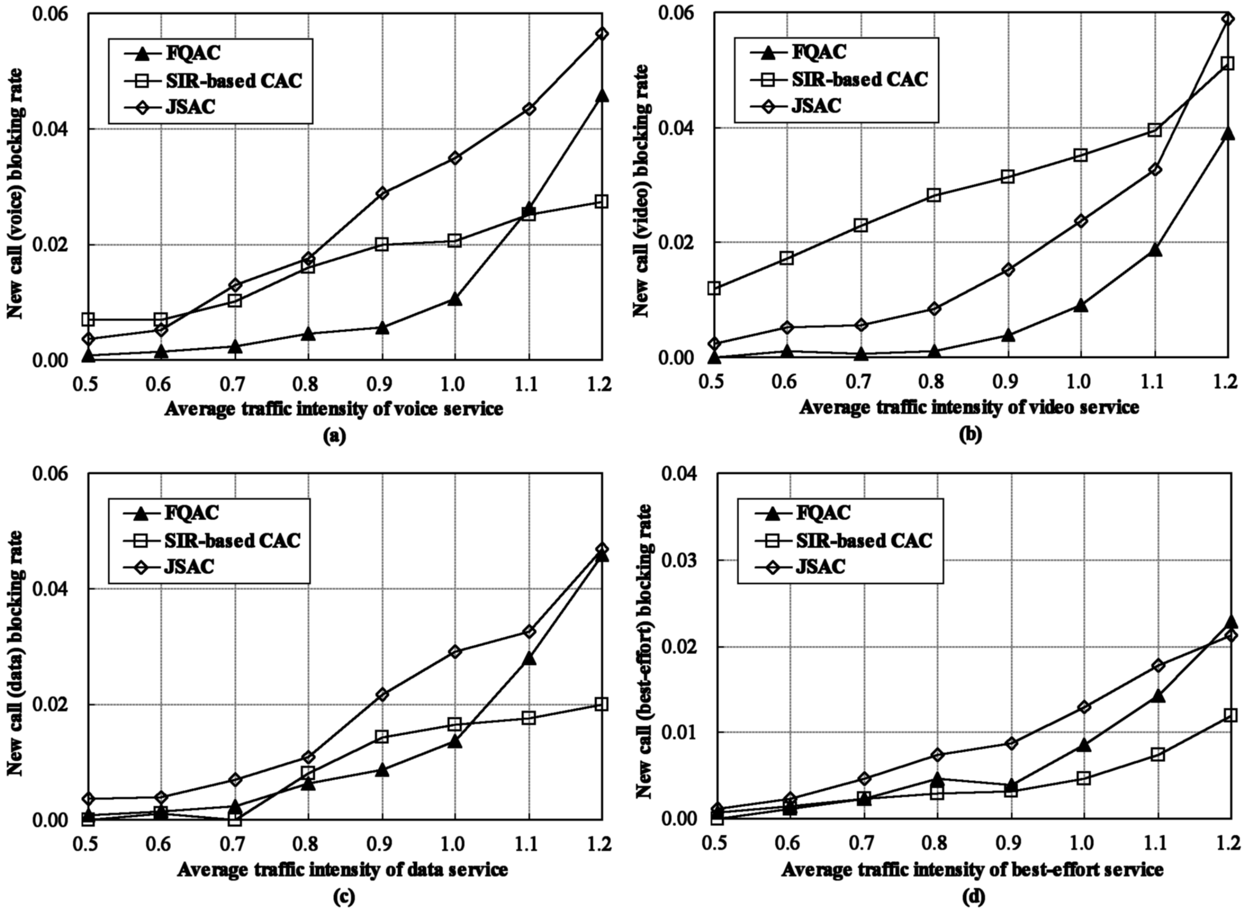


Figure 4.7: Average new user blocking rate for the service of (a) voice, (b) video, (c) data, and (d) best-effort

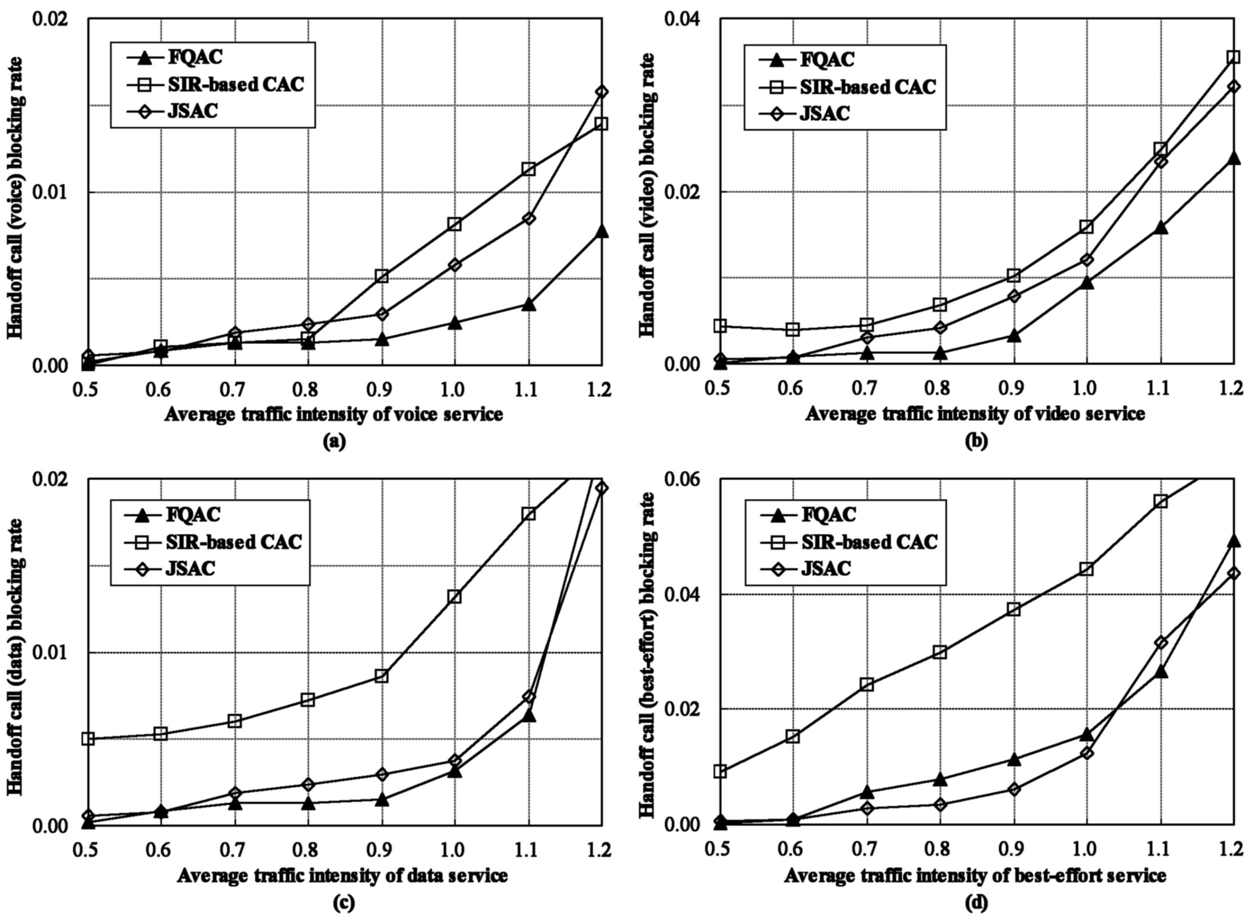


Figure 4.8: Average handoff user blocking rate for the service of (a) voice, (b) video, (c) data, and (d) best-effort

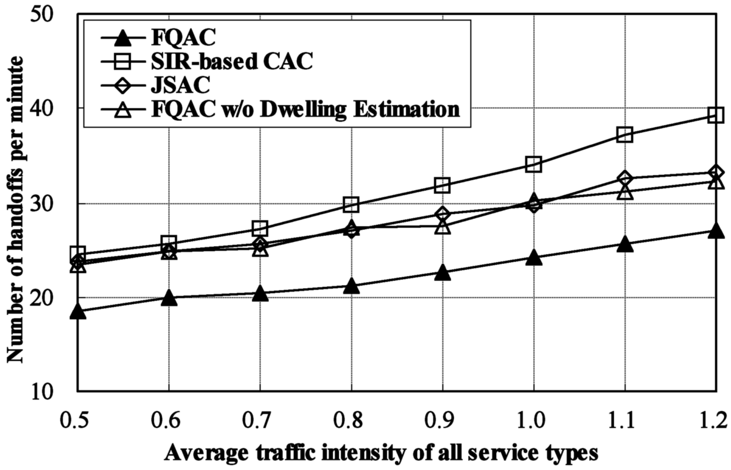


Figure 4.9: Average number of handoff per minute

versus the average traffic intensity. FQAC has sufficient low blocking rate to decrease the forced termination rate for the real-time services. This is because the dwelling estimation can avoid high-velocity users to enter the small-coverage subnetworks, and select the suitable subnetwork in which the mobile user dwell time is longer, as shown in Fig. 4.9. This is a great advantage to improve the user experience when using voice or video streaming services. Meanwhile, the systems' overhead of dealing with the handoff processes can be decreased. JSAC also has the same trend, but the forced termination rate would be somewhat higher because it does not consider the realistic channel variation and user mobility conditions. SIR-based CAC has the same problem mentioned above, and the property of admission decision with instant-measure also induces improper forced terminations.

## 4.5 Concluding Remarks

In this chapter, we propose *fuzzy Q-learning admission control* (FQAC) for WCDMA/ WLAN heterogeneous networks. The FQAC system adopts neural-fuzzy inference system (NFIS) with Q-learning (FQL) method for dwelling estimation and admissibility estimation. It considers multiple realistic system measures, such as the number of mobile users, interference in WCDMA systems, and the busy period in WLAN systems. Meanwhile, the QoS requirements and mobility of mobile users are also taken into account. According to these considerations, FQAC would generate the dwelling cost and admissibility cost in each reachable subnetwork to reflect the possible impact of the requesting mobile user. With FQL, the relations between system states and FQAC actions can be adaptively adjusted by a reinforcement learning signal measured from the states of every reachable network. In order to minimize the expected maximal impact (cost) of the mobile user's admission request, the decision maker in the FQAC system adopts minimax theorem to jointly estimate the mixed-cost and decide the most suitable subnetwork or reject the mobile user request. Simulation results show that FQAC performs more aggressive admission decisions than JSAC and SIR-based CAC when the traffic intensity is low. Hence FQAC has lower new and handoff user blocking rates and higher system utilization while maintaining the QoS. As long as the traffic intensity grows high, FQAC turns to be more conservative, and the blocking rates increase rapidly to avoid QoS violations. Since FQAC has the feature to estimate users mobility intelligently, the admitted subnetwork is also the one in which the user may dwell longer. This will lower the handoff rate, decrease the handoff blocking rate, and improve the real-time services user experience. And the mentioned performance of the FQAC system is the best evidence of that the FQAC system is capable to adapt to the fluctuation of traffic dynamics in the heterogeneous networks.

# Chapter 5

# Conclusions and Future Work

Call admission control (CAC) for WCDMA/WLAN heterogeneous networks is the major concern in this dissertation. Therefore the call admission control methods for WCDMA, WLAN, and WCDMA/WLAN heterogeneous networks with fuzzy techniques are accomplished. An efficient handoff method, named as the fast handoff protocol (FHP), is also proposed to provide fast and reliable handoff contention access in WLAN systems. These designs can help establish comprehensive call admission control in the WCDMA/WLAN heterogeneous networks. In order to handle more realistic situations in the wireless communication channels, the intelligent techniques based on fuzzy logic theorem are adopted. With the aid of fuzzy logic theorem, the designed admission controllers would behave more aggressive when the traffic load is light, and more conservative when the traffic load is becoming heavy to guarantee QoS of existing users.

First, an outage-based fuzzy call admission controller (OFCAC) with successive interference cancellation (SIC) multiuser detection (MUD) in WCDMA systems is proposed to handle the admission control. Since SIC can increase system capacity by eliminating home cell interference, the interference from other cells could be dominated. This property is carefully considered in the OFCAC for both new and handoff calls. In the proposed OFCAC with SIC in WCDMA systems, simulation results reveal that OFCAC-MUD without power control improves the system capacity by 70.5% as compared to an SIR-based CAC-RAKE with perfect PC. It also enhances the system capacity by 53.9% as compared to an OFCAC-RAKE with perfect PC, by 6.7% as compared to an SIR-based CAC-MUD without PC, and by 12.9% as compared to an OFCAC-MUD with perfect PC, given the same outage probability requirements. Moreover, OFCAC-MUD can prevent the violation of outage probability requirements in the hotspot environment, which is hardly achieved by SIR-based CAC.

Second, an intuitive scheduling and admission control (ISAC) with fast handoff protocol in cellular IEEE 802.11 WLAN systems is proposed. The ISAC handles the QoS admission requests by arranging the polling lists in the point coordination function (PCF). In order to provide a reliable handoff method in WLAN system, a fast handoff protocol (FHP) is also proposed. A dedicated period, the controlled contention period (CCP), for handoff requests (HO-REQs) is designed to eliminate the uncertainty of handoff delay in the cellular WLAN systems, and further a fuzzy adjustment method (FHM) is proposed to increase the utilization of CCP. In the proposed FHP for cellular IEEE 802.11 WLAN systems, it can decrease the forced termination rate of HO-REQs and still enhance the system throughput of CP. This major advantage brought by FHP, which eliminates the uncertainty of media access delay for HO-REQs, is significant. As a result, the WLAN systems can obtain more accurate time estimations for other pro-active procedures in the entire handoff process. This cannot be achieved by using enhanced distributed channel access (EDCA) method in the standards.

Finally, the admission control for WCDMA/WLAN interworking environment is achieved by using the proposed fuzzy Q-learning admission control (FQAC). The FQAC considers the mobility and QoS requirements of mobile users and the channel states of both systems. With Q-learning method, the FQAC can adaptively adjust itself intuitively to reach the best action and then determine the most suitable admission decisions in the WCDMA/WLAN heterogeneous networks. In the proposed FQAC for WCDMA/WLAN heterogeneous systems, simulation results show that FQAC can almost maintain the system QoS because it can appropriately admit or reject the users admission requests. The dwelling estimation can significantly reduce the number of handoffs, which makes FQAC to have lower handoff blocking probability in those real-time services.

There still exists room of improvement in these proposed designs. In the OFCAC with SIC in WCDMA, the power control could be an issue to affect the performance. Power control can resolve the near-far problem in uplink, but also degrade the interference suppression ability of SIC. As a result, the power control should be specially designed for SIC to obtain the optimal performance. Besides, the performance of interference cancellation could be further improved by using the *soft decision* method [94–96] because it loses information than the hard decision method. As a result, the signal can be regenerated more accurately, and the cancellation would be more complete.

In the ISAC with FHP, the QoS services are all arranged in the PCF duration in the WLAN systems. A more flexible design should include the enhanced distributed coordination function (EDCF), which allows the access points to declare the controlled access phase (CAP) in the distributed coordination function (DCF). With EDCF, there would be more room to schedule a services transmission opportunity (TXOP), but the designs would be more complicated, and the contention-based services would be affected.

The proposed FQAC provides an intelligent method for WCDMA/WLAN heterogeneous to select the available and the most suitable subnetwork for the mobile user. The decision maker can be further modified to support multi-link, multi-mode mobile devices. Based on the costs generated by the dwelling and admissibility estimations, a more complicated decision maker can be re-designed to allow a mobile user to be admitted in multiple subnetworks. Also, the minimax theorem is still a good choice for such mixed-strategy decisions. Therefore the FQAC can be upgraded to support soft-handoff, and its admission control will become more flexible in the heterogeneous networks.

All the proposed designs adopt fuzzy techniques. It is known that the expert domain knowledge for fuzzy logic systems is the kernel of its performance. Therefore OFCAC in WCDMA and FAM for FHP in WLAN need some prior works or investigations to obtain proper domain knowledge for fuzzy inference. FQAC uses the Q-learning, a kind of on-line reinforcement learning, to achieve automatic adaptation. The domain knowledge, however, is still required to reduce the learning rate. These are the issues for the call admission controllers to improve their efficiencies.

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