Fuzzy Q-Learning Admission Control for WCDMA/WLAN Heterogeneous Networks with Multimedia Traffic

Yung-Han Chen, *Member*, *IEEE*, Chung-Ju Chang, *Fellow*, *IEEE*, and Ching Yao Huang, *Member*, *IEEE*

Abstract—In this paper, admission control by a fuzzy Q-learning technique is proposed for WCDMA/WLAN heterogeneous networks with multimedia traffic. The fuzzy Q-learning admission control (FQAC) system is composed of a neural-fuzzy inference system (NFIS) admissibility estimator, an NFIS dwelling estimator, and a decision maker. The NFIS admissibility estimator takes essential system measures into account to judge how each reachable subnetwork can support the admission request's required QoS and then output admissibility costs. The NFIS dwelling estimator considers the Doppler shift and the power strength of the requested user to assess his/her dwell time duration in each reachable subnetwork and then output dwelling costs. Also, in order to minimize the expected maximal cost of the user's admission request, a minimax theorem is applied in the decision maker to determine the most suitable subnetwork for the user request or to reject. Simulation results show that FQAC can always maintain the system QoS requirement up to a traffic intensity of 1.1 because it can appropriately admit or reject the users' admission requests. Also, the FQAC can achieve lower blocking probabilities than conventional JSAC proposed in [20] and can significantly reduce the handoff rate by 15-20 percent.

Index Terms—Fuzzy Q-learning, admission control, handoff, heterogeneous network.

1 Introduction

The interworking functionality in heterogeneous environments 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 network and spectrum opportunity to select 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. For example, the wireless local area network (WLAN) [1] 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 support in high-mobility, low-latency services but it has lower data rate. The 3rd Generation Partnership Project (3GPP) has released a quite complete specification for WLAN interworking [2]. IEEE Task Group u is also standardizing the details of interworking with external networks [3].

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Manuscript received 1 May 2008; revised 16 Dec. 2008; accepted 3 Mar. 2009; published online 17 Mar. 2009.
For information on obtaining reprints of this article, please send e-mail to: tmc@computer.org, and reference IEEECS Log Number TMC-2008-05-0168. Digital Object Identifier no. 10.1109/TMC.2009.65.

Admission control is the first step of the system resource management in WCDMA/WLAN heterogeneous networks 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 [4] or WLAN only [5] 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 call admission request may have more than one option 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 call requests 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 [6] used a weighted cost function for each candidate network and formulated an optimization problem with criteria such as requirements of bandwidth, delay, and transmission power. Zhang [7] proposed a vertical handoff decision method by using multiple attributes, which was further solved by the fuzzy logic technique. Chen and Shu [8] proposed an active application oriented mechanism, which made the handoff decision according to a utility function. Song and Jamalipour [9] proposed a gray 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 a best decision selection, which outperforms traditional signal strength-based methods [10]. In addition, the factor of mobility, which combined the use of position-assisted and mobility prediction, was also considered for call admission control (CAC) in the work of Ye et al. [11]. However, these papers did not consider realistic dynamics of radio channels and network capabilities, which are essential to determine if the selected target cell is capable of providing service continuity for vertical handoff calls.

Some recent research also considered more comprehensive network selection problems in heterogeneous environments. Maldonado et al. [12] raised 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. [13] proposed a utility-based economic model to solve the resource allocation and the network selection problems in heterogeneous networks. Song et al. [14] investigated the WLAN-first call admission scheme for the cellular/WLAN interworking environment, which can achieve the maximum overall resource utilization. Suri and Narahari [15] proposed a novel auction algorithm for procuring wireless channel in heterogeneous networks. All of these works in [13], [14], [15] also focused on only the decision of a homogeneous 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. Lai and Tsai [16] studied three measurement-based CAC algorithms in heterogeneous environments. Service requirements are compared with measured system resource constrains to decide if the service request is admissible. Later, Huang and Ho [17] proposed a straightforward CAC for heterogeneous personal communications service (PCS). Two traffic types, real-time (RT) and non-real-time (NRT), were considered. The amounts of RT traffic and NRT traffic are compared with a predetermined channel occupancy threshold and the NRT buffer threshold, respectively, to determine the admission results. Song and Zhuang [18] 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 [19] proposed a cooperative method to consider three systems, IEEE 802.11 WLAN, CDMA cellular wireless access, and IEEE 802.16 WMAN, to provide a 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 [20] proposed joint session admission control (JSAC) to optimize the utilization of radio resources in integrated WLAN and CDMA networks. The QoS of WLAN (throughput and packet delay) and the QoS of CDMA (outage probability of signal-to-interference ratio (SIR)) were used to formulate the admission control problem as a semi-Markov decision process (SMDP). With a linear programming method, the admission decision is made according to the QoS state. However, the JSAC does not consider the service types, the rapid state changes caused by channel variation, and the user mobility in such a stochastic-based method.

These mentioned works considered the essential QoS requirements such as data rate, delay bound, and 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, effective call admission control should periodically monitor system status such as the number of users, interference in WCDMA, network busy periods in WLAN, etc. Also, it has to be aware of QoS requirements of multimedia traffic and mobility of users to make the most proper decision for a user's admission request.

In this paper, we propose *fuzzy Q-learning admission control* (FQAC) for WCDMA/WLAN heterogeneous networks. The FQAC considers not only QoS requirements but also multiple system measures such as interferences from home cells and other adjacent cells, the numbers of real-time and non-real-time users in the system, and user's mobility. In order to put all the system measures and QoS requirements together for an admission request, the FQAC is designed to contain an admissibility estimator, a dwelling estimator, and a decision maker. The FQAC adopts a fuzzy Q-learning (FQL) method [21], [22] for estimation and a minimax theorem [23] for decision making, where the FQL integrates the neural-fuzzy inference system (NFIS) [24], [25] with the online Q-learning algorithm. The Q-learning has been proven to converge to a global optimum in the Markov decision process with simplicity of iteratively computational demands [21]. With the system measures and the user's profile, the NFIS will take an action, which is the estimated cost of the admission request, for each reachable network. Then, the decision maker collects the costs and makes a final admission/rejection decision by using the minimax theorem. The possible actions taken by the NFIS are tuned by FQL, which can simplify the reinforcement learning procedure and increase the feasibility and scalability in real implementation. Without the knowledge of system state-transition probability, the FQL can iteratively and adaptively adjust the relations between system states and actions by reinforcement learning signals feedbacked from the system. The complexity of FQAC is low, which is feasible and will be a great advantage in reducing the vertical handoff latency.

Simulation results show that FQAC performs more aggressive admission control than JSAC in [20] when the traffic intensity is low, and FQAC turns to be more prudential when the traffic intensity grows high. Hence, FQAC has

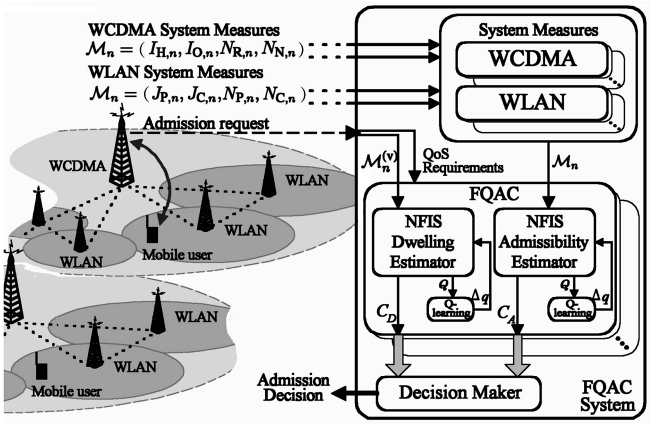

Fig. 1. The heterogeneous networks and the FQAC system.

lower new and handoff user blocking rates and higher system utilization while maintaining the QoS requirements. It is because FQAC has features to intelligently estimate user's admissibility and dwelling time. FQAC also achieves lower handoff rate than JSAC for the reason that the admitted (cell) subnetwork would be the one in which the user may dwell longer. Moreover, once the initial training is completed, the online convergence rate of FQAC is fast, which is about 11 episodes (about 850 milliseconds) in average and is feasible for real implementation and applications.

The organization of this paper is as follows: In Section 2, the system model for a WCDMA/WLAN heterogeneous network is described, and the essential system measures are selected. Section 3 presents the proposed approach of FQAC. Section 4 illustrates simulation results. Finally, Section 5 draws the conclusions.

2 System Model

Fig. 1 shows the WCDMA/WLAN heterogeneous network with FQAC, which is installed in the radio network controller (RNC). Each WCDMA or WLAN system is a *subnetwork* of the heterogeneous network. Generally speaking, the subnetwork is deployed with its strategy of topology, and these subnetworks could be overlapped with each other.

Denote S as a set of all reachable subnetworks of a call request of a mobile user. This implies that the pilot or the beacon of the nth subnetwork in S, denoted by S_n and $S_n \in S$, 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 [26]. The most commonly used processes of fading and shadowing are in Rayleigh and log-normal distributions, respectively, which reflect influences from user's movement and geographical obstacles [27], [28].

2.1 WCDMA System Measures

According to specifications of PHY and MAC in the WCDMA system [29], [30], 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 10 ms with spreading factor of 256 in DPCCH and 4-256 in DPDCH. In WCDMA subnetwork S_n, a four-tuple vector of essential system measures, denoted by $\mathcal{M}_n$, is appropriately chosen for admissibility estimation of a call request. The $\mathcal{M}_n$ is given by

$$\mathcal{M}_n = (I_{\mathrm{H},n}, I_{\mathrm{O},n}, N_{\mathrm{R},n}, N_{\mathrm{N},n}), \tag{1}$$

where $I_{\mathrm{H},n}$ ($I_{\mathrm{O},n}$) is the home-cell (other-cell) interference, and $N_{\mathrm{R},n}$ ($N_{\mathrm{N},n}$) is the total number of real-time (non-real-time) users. Notice that the WCDMA is an interference-constraint system. If the interference is larger, the existing system load is higher and the available system capacity is lower. Therefore, $I_{\mathrm{H},n}$ and $I_{\mathrm{O},n}$ are chosen to evaluate the residual system capability for the WCDMA system. $N_{\mathrm{R},n}$ and $N_{\mathrm{N},n}$ can further reflect the current system loading directly. These measures can always be obtained according to 3GPP standards such as TS 25.215, TS 25.225, and TS 25.922 [31], [32], [33].

2.2 WLAN System Measures

Major standards of the WLAN system [1], [34], [35] define PHY, MAC, and amendments protocols over 2.4 GHz and 5 GHz bands. In the paper, the infrastructure mode is assumed; the beacon interval (BI) is set to 20 ms, 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 network is tightly coupled [2], [36], the admission request of a user for RNC is also through the PRACH to determine to use CFP or CP of the WLAN subnetwork. Similarly, in WLAN subnetwork S_n, a four-tuple vector of essential system measures $\mathcal{M}_n$ is appropriately selected for admissibility estimator of a call request. The $\mathcal{M}_n$ is given by

$$\mathcal{M}_n = (J_{\mathrm{P},n}, J_{\mathrm{C},n}, N_{\mathrm{P},n}, N_{\mathrm{C},n}), \tag{2}$$

where $J_{\mathrm{P},n}$ is the percentage of busy period in CFP per BI, $J_{\mathrm{C},n}$ is the ratio between the period of successful transmission and the busy period in CP per BI, and $N_{\mathrm{P},n}$ ($N_{\mathrm{C},n}$) is the total number of users in CFP (CP). Notice that $J_{\mathrm{P},n}$ and $J_{\mathrm{C},n}$ can somewhat represent the existing loading of the WLAN system in CFP and CP, respectively. $J_{\mathrm{C},n}$ also includes the collision characteristic of WLAN in CP. If $J_{\mathrm{C},n}$ is low, it means that there is a lot of unsuccessful transmissions due to collisions or other errors. $N_{\mathrm{P},n}$ and $N_{\mathrm{C},n}$ are another information to judge the current system loading. All these measures can be obtained by means of signal/power detection and computation, accumulating the valid number of association ID, or the available methods in the standards of IEEE 802.11k/D13.0 [37] and IEEE P802.11.2/D1.01 [38].

2.3 Admission Request

Assume that each mobile user is equipped with dual modules of WCDMA and WLAN. 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 [39] 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 the minimum data rate (R^*), the maximum delay (D^*), and the maximum bit error rate (ϵ^*). The mobility measures in the admission request for S_n originally choose the received pilot (beacon) strength, $\tilde{P}_n$, and the detected *Doppler shift*, $\tilde{f}_n$. If $\tilde{P}_n$ is large (small), it denotes that the location of user is near the BS (cell boundary). The $\tilde{f}_n$ is equal to $(v \cos\theta_n)/\lambda_n$ [26], where v is the velocity of the user, θ_n is the angle between the user's moving direction and the straight line from user to the BS of S_n, and λ_n is the wavelength of carrier frequency in S_n. If the measured $\tilde{f}_n$ is positive (negative), it denotes that $\cos\theta_n$ is positive (negative) and the user is approaching (leaving) BS. Thus, it can be concluded that the detected Doppler shift can represent the relative, geographical movement relationship between the user and the BS. This Doppler shift, $\tilde{f}_n$, with $\tilde{P}_n$ can estimate the possible dwelling duration of user in S_n. Therefore, a two-tuple vector of measures for dwelling duration estimation, denoted by $\mathcal{M}_n^{(\mathrm{v})}$, is given by

$$\mathcal{M}_n^{(\mathrm{v})} = (\tilde{f}_n, \tilde{P}_n). \tag{3}$$

3 Design of FQAC

The FQAC system, as shown in Fig. 1, consists of two NFISs for *admissibility estimator* and *dwelling estimator* and a decision maker. Every NFIS is configured by a five-layered structure for fuzzy logics, and adopts an FQL method [21], [22], [40] 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 (1), (2), (3), and QoS requirements. Its advantage is that the Bellman optimality in the learning process can be achieved without knowing the state-transition behaviors [21]. The FQAC can determine the most suitable subnetwork among all reachable subnetworks for a mobile user's call admission request.

3.1 Fuzzy Q-Learning Method

In the FQL method, there are a set of state vectors, denoted by $\Phi = \{\phi_i, i = 1, 2, \ldots, M\}$, and a set of actions, denoted by $\boldsymbol{A} = \{A_j, j = 1, 2, \ldots, N\}$. Also, each fuzzy inference rule is made by the form of

IF *input state vector* $\mathbf{x}$ is ϕ_i,
THEN the *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 [24], [41], [42]. To defuzzify the M fuzzy rules, the inferred action for $\mathbf{x}$, denoted by $V(\mathbf{x})$, is defined as

$$V(\mathbf{x}) = \frac{\sum_{i=1}^{M} w_i A_i}{\sum_{i=1}^{M} w_i}, \tag{4}$$

where w_i is the truth value of rule corresponding to ϕ_i. According to [21], 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

$$Q(\mathbf{x}, V(\mathbf{x})) = \frac{\sum_{i=1}^{M} w_i \cdot q(\phi_i, A_i)}{\sum_{i=1}^{M} w_i}. \tag{5}$$

A reinforcement signal, denoted by $r(\mathbf{x}, V(\mathbf{x}))$, is used 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

$$Q^*(\hat{\mathbf{x}}, V(\hat{\mathbf{x}})) = \frac{\sum_{i=1}^{M} w_i \cdot q(\phi_i, A_i^*)}{\sum_{i=1}^{M} w_i}, \tag{6}$$

where

$$A_i^* = \arg\max_{A_j} \{q(\phi_i, A_j)\}. \tag{7}$$

Then, the Q-value will be updated by

$$q(\phi_i, A_i) = q(\phi_i, A_i) + \eta \Delta q(\phi_i, A_i), \tag{8}$$

where

$$\Delta q(\phi_i, A_i) = \frac{w_i}{\sum_{h=1}^{M} w_h} \cdot (r(\mathbf{x}, V(\mathbf{x})) + \gamma Q^*(\hat{\mathbf{x}}, V(\hat{\mathbf{x}})) - Q(\mathbf{x}, V(\mathbf{x}))), \tag{9}$$

$\eta \in [0, 1]$ is the learning rate, and $\gamma \in [0, 1]$ is the discount factor used for the reinforcement signal $r(\mathbf{x}, V(\mathbf{x}))$. The FQL can converge to a global optimum for a given optimization problem on the inferred action $V(\mathbf{x})$ [21], [22], [40]. The FQAC method has the capability to iteratively approximate the unknown optimal $V(\mathbf{x})$ between inputs and outputs and to track time variations of input statistics. It takes a balanced position between the learning convergence speed and the convergence accuracy. In addition, FQL has the simplicity of implementation by software or hardware.

3.2 NFIS Admissibility Estimator

The NFIS admissibility estimator is designed to investigate how much the admittance of the new or handoff user's call admission request affects the QoS of existing connections. It evaluates the admissibility of the user with QoS requirements including data rate (R^*), delay (D^*), and bit error rate (ϵ^*) in the subnetwork $S_n, \forall S_n \in \boldsymbol{S}$. For S_n, the input state vector $\mathbf{x}$ of the NFIS admissibility estimator is designated to be $\mathcal{M}_n$ and $\mathcal{M}_n = (I_{\mathrm{H},n}, I_{\mathrm{O},n}, N_{\mathrm{R},n}, N_{\mathrm{N},n})$ given in (1) if S_n belongs to WCDMA system or $\mathcal{M}_n = (J_{\mathrm{P},n}, J_{\mathrm{C},n}, N_{\mathrm{P},n}, N_{\mathrm{C},n})$ given in (2) if S_n belongs to WLAN

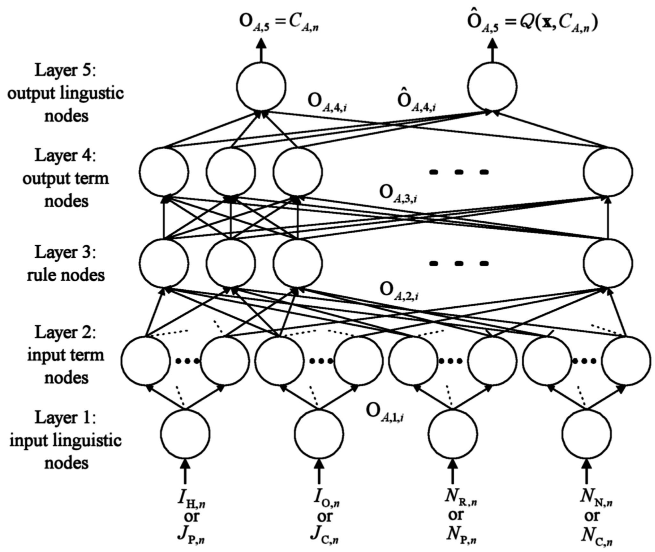

Fig. 2. A five-layered NFIS admissibility estimator for subnetwork S_n.

system. The output action $V(\mathbf{x})$ for S_n, denoted by $C_{A,n}$, is the *admissibility cost* if the call request is accepted by S_n. The lower $C_{A,n}$ implies the higher admissibility of the call request by S_n. There are four input linguistic variables from $\mathcal{M}_n$. Each linguistic variable, $L_n \in \mathcal{M}_n$, assumes an 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 $|\mathrm{T}(L_n)|^4 = 256$. The fuzzy term set of $C_{A,n}$ is 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 the NFIS admissibility estimator is defined as

$$\begin{aligned} r(\mathbf{x}, V(\mathbf{x})) &= r(\mathcal{M}_n, C_{A,n}) \\ &= \left[\frac{(R^* - \tilde{R}(\mathcal{M}_n, C_{A,n}))^+}{R^*}\right]^2 \\ &\quad + \left[\frac{(\tilde{D}(\mathcal{M}_n, C_{A,n}) - D^*)^+}{D^*}\right]^2 \\ &\quad + \left[\frac{(\tilde{\epsilon}(\mathcal{M}_n, C_{A,n}) - \epsilon^*)^+}{\epsilon^*}\right]^2, \end{aligned} \tag{10}$$

where $(a)^+$ represents the operation $\max(a, 0)$, $\tilde{R}(\mathcal{M}_n, C_{A,n})$, $\tilde{D}(\mathcal{M}_n, C_{A,n})$, and $\tilde{\epsilon}(\mathcal{M}_n, C_{A,n})$ are the values of data rate, delay, and bit error rate measured from system statistics under the state-action pair $(\mathcal{M}_n, C_{A,n})$, respectively. R^*, D^*, and ϵ^* are the QoS requirements of the call request. We construct a five-layered NFIS admissibility estimator for subnetwork S_n. As shown in Fig. 2, the function of each layer of the NFIS admissibility estimator is described as follows.

Layer 1 is the input layer with four input linguistic nodes. Every node is a bell shaper of L_n with four identity outputs to the next layer. Hence, there are total 16 outputs, which are expressed as

$$\mathrm{O}_{A,1,i} = \exp\left\{\frac{-(L_n - \mu)^2}{2\mu^2}\right\}, \forall L_n \in \mathcal{M}_n,\ i = 1, 2, \ldots, 16, \tag{11}$$

where μ is a constant for bias given by every subnetwork. Note that nodes 1-4 (5-8) (9-12) (13-16) 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. 2. Each node i, with input $\mathrm{O}_{A,1,i}$, plays the role of the membership function in the NFIS. The membership function in node i applies the trapezoid function, which is given by

$$G_i(m) = \begin{cases} \dfrac{m - m_{i,1}}{m_{i,2} - m_{i,1}}, & m_{i,1} \le m \le m_{i,2}, \\ 1, & m_{i,2} \le m \le m_{i,3}, \\ \dfrac{m_{i,4} - m}{m_{i,4} - m_{i,3}}, & m_{i,3} \le m \le m_{i,4}, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

where $m_{i,1}$ and $m_{i,4}$ ($m_{i,2}$ and $m_{i,3}$) represent two terminals of the lower (upper) parallel sides of the trapezoid. Thus, the output of node i can be expressed as

$$\mathrm{O}_{A,2,i} = G_i(\mathrm{O}_{A,1,i}), \quad i = 1, 2, \ldots, 16. \tag{13}$$

Layer 3 is the rule node layer. This layer implements the truth value of NFIS with a fuzzy-AND operator, and node i represents the behavior of rule i with preconditioned involvement of node j over *Layer 2*. Since the NFIS admissibility estimator has four input linguistic variables, each node over this layer has four inputs. With product operation, the output of node i can be expressed as

$$\mathrm{O}_{A,3,i} = \prod\{\mathrm{O}_{A,2,j}\}, \quad i = 1, 2, \ldots, 256, \tag{14}$$

where j is the node index over layer 2 that is used in the ith rule.

Layer 4 is the output layer. Each node in this layer is an action-select node which represents the consequence part of the ith fuzzy rule. Based on the action selection policy and Q-values of the possible action candidates in $\mathrm{T}(C_{A,n})$, the node is to choose an appropriate action. In order to obtain a better learning result due to improper initial setting of fuzzy rules, the *semiuniform distributions* strategy in [24], [42] is employed to explore the set of all possible actions. Therefore, the node $i, i = 1, 2, \ldots, 256$ over this layer will first select an action A_i for the (ϕ_i, A_i) pair with the probability given by

$$P(\phi_i, A_i) = \begin{cases} P^*(\phi_i, A_i^*) + \dfrac{1 - P^*(\phi_i, A_i^*)}{|\mathrm{T}(C_{A,n})|}, & \text{if } A_i = A_i^*, \\ \dfrac{1 - P^*(\phi_i, A_i^*)}{|\mathrm{T}(C_{A,n})|}, & \text{otherwise}, \end{cases} \tag{15}$$

where A_i^* can be obtained by (7), $P^*(\phi_i, A_i^*)$ is a predefined 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 actions, one of them will be selected randomly. This semiuniform 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 will generate two outputs with normalization, which can be expressed by

$$\mathrm{O}_{A,4,i} = \frac{\mathrm{O}_{A,3,i} \times A_i}{\sum_{\ell=1}^{256} \mathrm{O}_{A,3,\ell}}, \quad (16)$$

and

$$\hat{\mathrm{O}}_{A,4,i} = \frac{\mathrm{O}_{A,3,i} \times q(\phi_i, A_i)}{\sum_{\ell=1}^{256} \mathrm{O}_{A,3,\ell}}. \quad (17)$$

Equations (16) and (17) are the action-weighted and Q-value-weighted consequences of fuzzy rule i for the next layer.

Layer 5 decides the admissibility cost of $S_n, C_{A,n}$, and the Q-value of the state-action vector pair $(\mathbf{x}, V(\mathbf{x})), Q(\mathbf{x}, V(\mathbf{x}))$. They are accomplished by a *center of area* (COA) defuzzification method [24]. The outputs are given by

$$\mathrm{O}_{A,5} = C_{A,n} = \sum_{i=1}^{256} \mathrm{O}_{A,4,i} \quad (18)$$

and

$$\hat{\mathrm{O}}_{A,5} = Q(\mathcal{M}_n, C_{A,n}) = \sum_{i=1}^{256} \hat{\mathrm{O}}_{A,4,i}. \quad (19)$$

Afterward, the $\tilde{R}(\mathcal{M}_n,C_{A,n})$, $\tilde{D}(\mathcal{M}_n,C_{A,n})$, and $\tilde{\epsilon}(\mathcal{M}_n,C_{A,n})$ in (10) can be measured, the reinforcement signal $r(\mathbf{x}, V(\mathbf{x}))$ can be obtained, and the corresponding Q-value in (8) and (9) can be updated. Notice that the NFIS admissibility estimator can be regarded as a single-agent learner. Each single subnetwork has its own database of the Q-value update and action selection probability for every mobile user. Therefore, its learning will be converged with rate and precision affected by learning rate η and the exploration strategy.

3.3 NFIS Dwelling Estimator

The NFIS dwelling estimator is to evaluate the possible dwelling time duration of the user's call admission request in the subnetwork $S_n, \forall S_n \in \boldsymbol{S}$. For S_n, the input state vector $\mathbf{x}$ of the NFIS dwelling estimator is designated to be $\mathcal{M}_n^{(\mathrm{v})} = (\tilde{f}_n, \tilde{P}_n)$ which is given in (3). The output action $V(\mathbf{x})$ is a *dwelling cost*, denoted by $C_{D,n}$. If the dwelling time duration is longer, the dwelling cost is lower. The two input linguistic variables are with fuzzy term sets designed 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 is $|\mathrm{T}(\tilde{f}_n)| \times |\mathrm{T}(\tilde{P}_n)| = 20$. The inferred output action $C_{D,n}$ is 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 designed as

$$r(\mathbf{x}, V(\mathbf{x})) = r\big(\mathcal{M}_n^{(\mathrm{v})}, C_{D,n}\big) = \left[\frac{\big(c\xi - \tau\big(\mathcal{M}_n^{(\mathrm{v})}, C_{D,n}\big)\big)^+}{c\xi}\right]^2, \quad (20)$$

where $\tau(\mathcal{M}_n^{(\mathrm{v})}, C_{D,n})$ is the actual average dwell time of users measured under $(\mathcal{M}_n^{(\mathrm{v})}, C_{D,n})$ pair, ξ is the maximum handoff delay bound defined by the system, and $c > 1$ 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 the next handoff and prevent from too frequent handoffs.

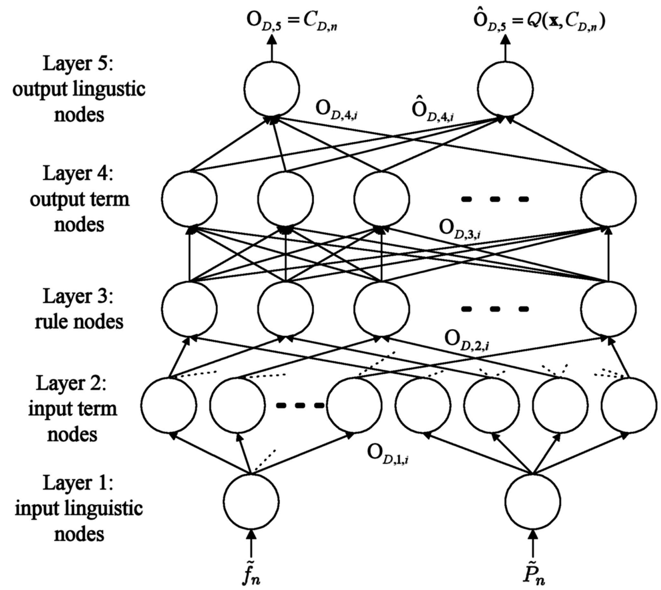

Fig. 3. A five-layered NFIS dwelling estimator for subnetwork S_n.

Also, as shown in Fig. 3, a five-layered NFIS dwelling estimator is constructed for subnetwork S_n. The function of each layer of the NFIS dwelling estimator is similar to that of the NFIS admissibility estimator. For its detailed design, please refer to [43]. With the reinforcement signal in (20), the learning update for action selection in the NFIS dwelling estimator can be calculated by (8) and (9). In the design, each single subnetwork has its own database of the Q-value update and action selection probability for every type of service. Similarly, the learning rate η and the exploration strategy would influence the convergence performance of Q-learning.

3.4 The Decision Maker

The decision maker in the FQAC system, shown in Fig. 1, makes the admission decision based on a *minimax* theorem [23]. The minimax theorem is an optimal approach for mixed strategies in the statistical decision theory and the zero-sum game theory proved by Jonas von Neumann in 1928. According to the minimax theorem, the expected maximum costs of all reachable subnetworks, which is represented by the admissibility and dwelling costs, can be minimized for the admission decision. Therefore, the optimally chosen subnetwork m for the new or handoff user has to satisfy

$$m^* = \arg\min_m\{\max\{C_{A,m}, C_{D,m}\}\}. \quad (21)$$

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, the FQAC system will reject the user's admission request.

The ultimately selected subnetwork is the one with the minimal cost among all possible maximal costs. The decision will lead the FQAC to behave more aggressive

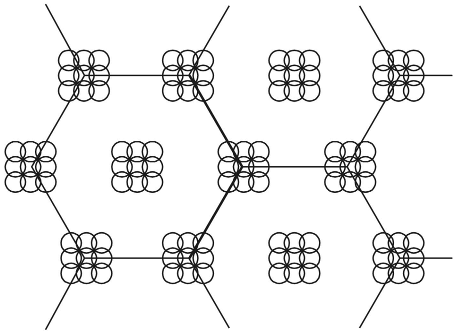

Fig. 4. The topology of WCDMA/WLAN heterogeneous networks for simulations.

when the overall load is light and more prudential when the overall load is heavy to ensure QoS guarantee.

4 Simulation Results

4.1 Simulation Environment

The simulations consider a WCDMA system containing 7×7 hexagonal and wrap-around WCDMA cells for simulations. The longest distance between the BS and the cell boundary is 1 kilometer. The channel of the WCDMA system suffers intercell MAI, intracell MAI, AWGN noise, log-normal shadowing [44], and multipath fading [45]. The path-loss exponent is 4.35 [27], and the spreading factor is from 4 to 256. Perfect power control is used in the system. As shown in Fig. 4, the WLAN subnetworks are overlapped over the WCDMA networks. A WLAN subnetwork group consists of 3×3 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 three 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 [34], [35], where the SIFS, PIFS, and DIFS are assumed to be 10, 20, and $40\ \mu s$, respectively; a beacon interval is 20 ms; the maximum duration of CFP is 15 ms; and a slot time (aSlotTime) of PHY is $9\ \mu s$. The value of ξ and constant c in (20) are 500 ms and 3, respectively. In order to eliminate the handoff latency of the handoff request contention in the WLAN system, the *fast handoff protocol* in [46] is adopted to provide efficient inter-AP transitions.

The arrival of new calls in each WCDMA cell is modeled as a Poisson process with a mean arrival rate λ. The traffic intensity is defined as the product of the mean arrival rate and the mean session time of a call. There are four types of traffic in the WCDMA/WLAN heterogeneous network: real-time voice, real-time video stream, non-real-time data, and best effort. In the simulations, a new call could be a voice call, video call, data call, and best effort call with the possibility of 30, 20, 40, and 10 percent, respectively. Users are also assumed to be uniformly distributed in cells, and a random-walk model is used to simulate the mobility of every user. Four kinds of mobility, fixed, pedestrian, medium velocity, and high velocity, are modeled with mean speed 0, 5, 40, and 80 kilometers per hour in distribution 35, 35, 20, and 10 percent, respectively. Similarly, all mobile users in WLAN are located randomly and activated in a saturation mode of that their access transmissions are always on. The system QoS requirements are listed in Table 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). Also, the simulations are based on the Monte Carlo method, and the design of the FQAC is implemented with referring to the Reinforcement Learning Toolbox [47].

TABLE 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}

4.2 Simulation Results

Fig. 5 depicts the mean QoS guarantee ratios of the proposed FQAC and the JSAC in [20] for all services versus the traffic intensity, where the 95 percent confidence intervals are also provided at traffic intensity 0.8 and 1.0. It can be found that the FQAC can maintain almost all services' QoS requirements when the traffic intensity is as high as 1.1. The reasons are that FQAC adopts the combination of fuzzy logic and neural network with Q-learning to provide the capability to adapt to system dynamics, also FQAC chooses significant system measures and appropriately makes decision to admit or reject the admission requests by the intelligent FQL method and the minimax theorem. The JSAC, however, has a few QoS violations at high traffic intensity, and has apparent degradation performance when the traffic becomes very intense. It is because some short-term system state variations cannot be reflected in its CAC method and the improper admission decisions might occur.

Fig. 6 depicts the new call blocking rates of four service types versus the average traffic intensity, where the 95 percent confidence intervals at traffic intensity 0.8 and

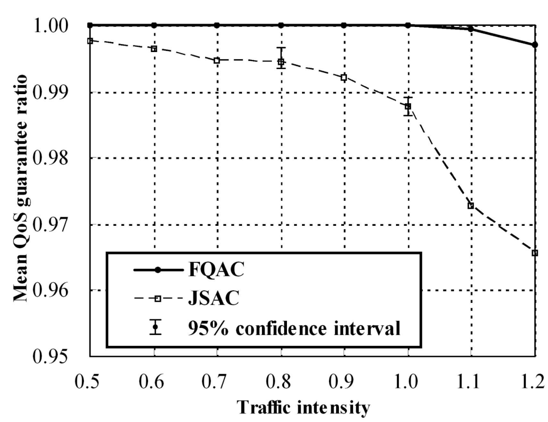

Fig. 5. Mean QoS guarantee ratio.

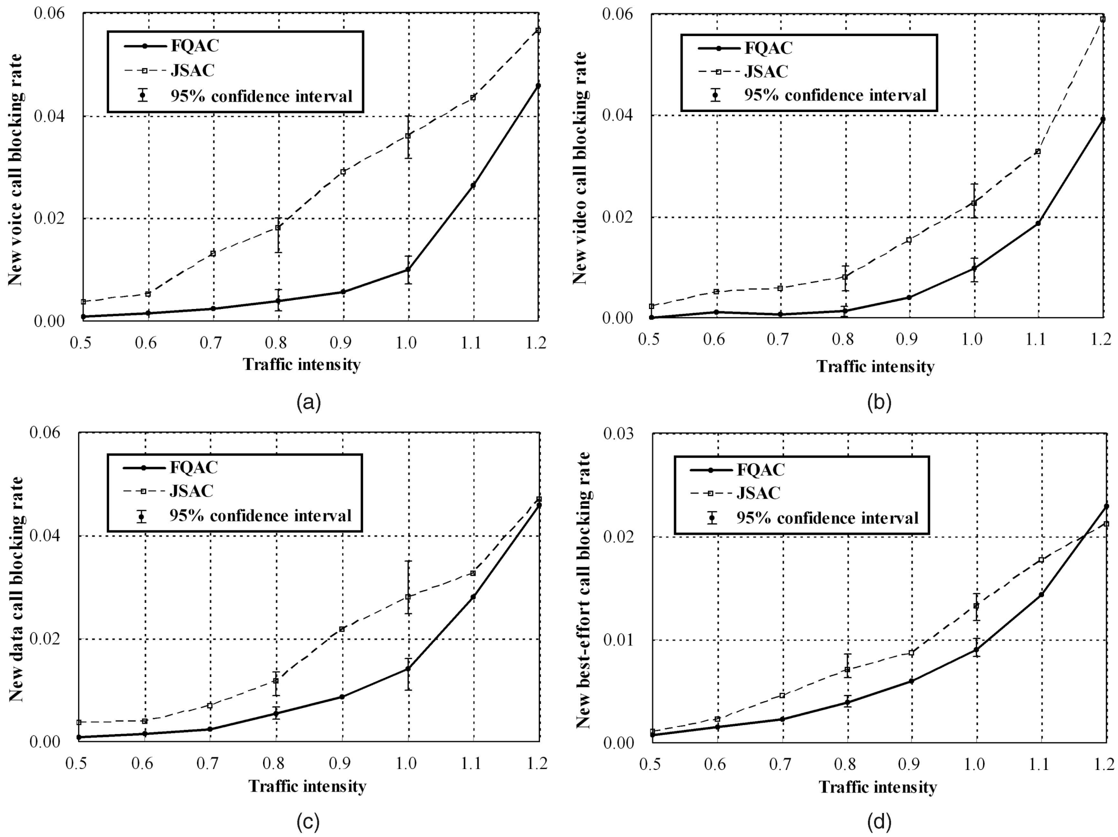

Fig. 6. New call blocking rate for the service of (a) voice, (b) video, (c) data, and (d) best effort.

1.0 are also included. It can be found that FQAC has lower average new call blocking rate lower than JSAC. The reason is that the FQAC considers more realistic, essential system measures and user mobility in both WCDMA and WLAN systems. The system states can be reflected to the admission decisions. In addition, the FQL method is capable of adapting to system variation with the self-learning ability. Therefore, the system with FQAC will be able to accommodate more users and make better admission decisions while maintaining QoS guarantee. However, when the traffic intensity is extremely high, the slope of new call blocking rate of FQAC will become sharp, which represents that the FQAC becomes prudential to reject the new call to prevent system overflow and keep QoS guaranteed. JSAC, however, uses statistical parameters as the basis of admission control, it might not be able to catch the short-term system changes and result in some improper admission decisions. In order to keep the ratio, the QoS guarantee as high as possible, JSAC has to leave a margin to mitigate the influence of channel variation and user mobility; this would sacrifice the precision of CAC and system capacity.

Fig. 7 shows the handoff call blocking rates for four service types versus the traffic intensity and the 95 percent confidence intervals at 0.8 and 1.0. In order to lower the forced termination rate of on-going calls, it is necessary to design the system with the handoff call blocking rate lower than the new call blocking rate. It can be found that FQAC can generally attain the handoff blocking rate smaller than JSAC in the QoS services of voice, video, and data. This implies that FQAC would have lower forced termination rate for these QoS services. The most important reason is that FQAC is designed with an NFIS dwelling estimator to avoid high-velocity users entering small-coverage subnetworks and select the suitable subnetwork in which the mobile user dwell time is longer. There are some overlaps of confidence intervals in these figures, where FQAC may attain handoff call blocking rate larger than JSAC. However, the probabilities that FQAC performs worse than JSAC in those overlapping areas are below 0.1 percent except in Figs. 7b and 7c with traffic intensity 1.0, in which the probabilities are about 10 percent.

We can also see from Fig. 8 that FQAC has the smallest handoff rate. With the NFIS dwelling estimator, the number of handoff in FQAC can be significantly reduced by 15-20 percent as compared to JSAC and FQAC if without dwelling estimator. 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 process can be decreased. It is because FQAC without dwelling estimator cannot prevent a high-velocity or mobile-through user to be admitted to a small subnetwork. Also, JSAC does not consider the realistic channel variation and user mobility conditions.

Finally, we also observe the convergence performance of FQAC in the simulations. The initial training requires about 98 iterations in average to converge. Once the initial training is finished, the online learning takes 11 iterations at most to converge. The convergence time is about 850 milliseconds, which is quick enough for the online learning of an admission controller.

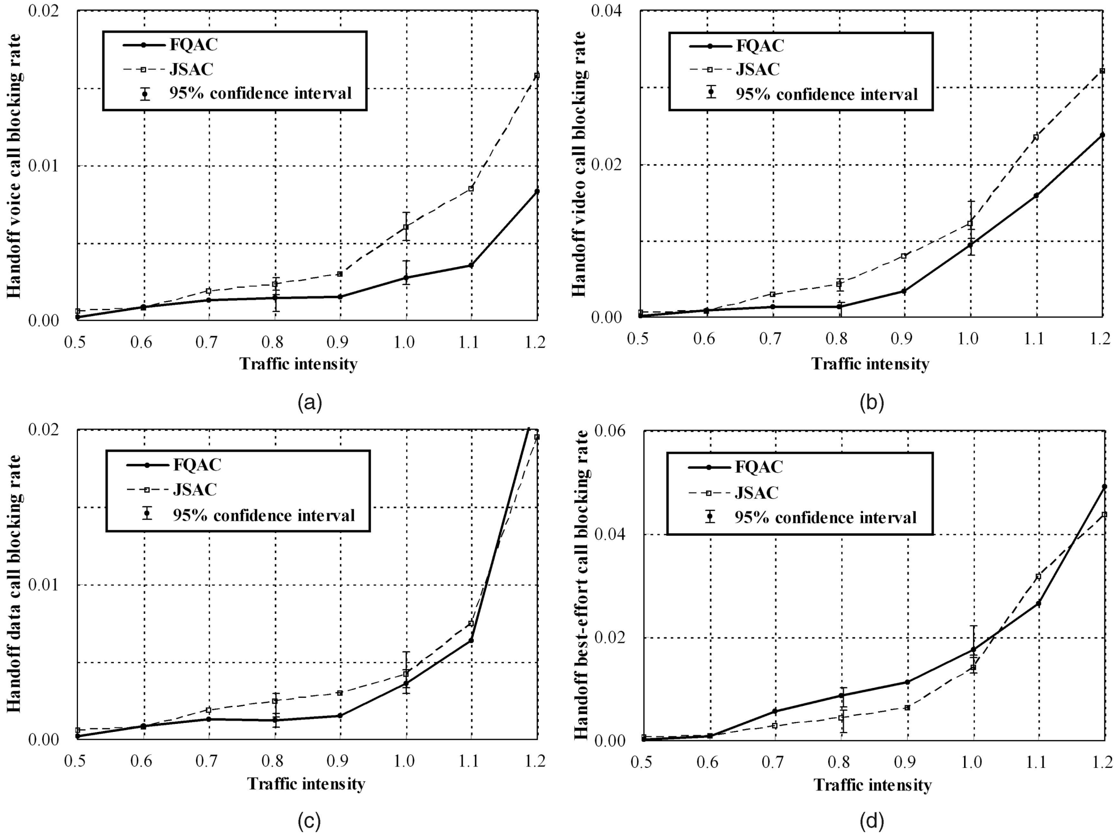

Fig. 7. Handoff call blocking rate for the service of (a) voice, (b) video, (c) data, and (d) best effort.

5 Conclusions

In this paper, we propose *FQAC* for multimedia traffic in WCDMA/WLAN heterogeneous networks. The FQAC system adopts a NFIS with Q-learning (FQL) method for admissibility estimator and dwelling estimator. Generally, the fuzzy logic technology can provide a robust mathematical method for admission control in realistic environments, especially when the mathematical model of the process is too complicated to find. The combination of fuzzy logic and neural network with Q-learning further provides the ability to adapt to system dynamics because it can automatically adjust the relations between system states and actions which exist in the fuzzy rules. Also, the FQAC system considers essential system measures as input linguistic variables, such as the number of mobile users, the interference in WCDMA systems, and the busy period in WLAN systems. Meanwhile, the QoS requirements and the mobility of the user's admission request are taken into account. According to these linguistic variables, FQAC would generate the admissibility cost and dwelling cost of each reachable subnetwork to reflect the impact of these subnetworks by the user's admission request. In order to minimize the expected maximal impact (cost) of the mobile user's admission request, the decision maker in the FQAC system adopts the minimax theorem to jointly estimate the mixed cost and decides the most suitable subnetwork or reject the mobile user request.

Simulation results show that FQAC performs more aggressive admission control than JSAC when the traffic intensity is low. However, whenever the traffic intensity grows high, FQAC turns to be more prudential to avoid QoS violations. Hence, FQAC has lower new and handoff user blocking rates, while maintaining the QoS. Also, the FQAC can significantly reduce the average number of handoff by 15-20 percent as compared to JSAC. The FQAC system would be capable to adapt to the fluctuation of traffic dynamics and should be one of the best choices for heterogeneous networks.

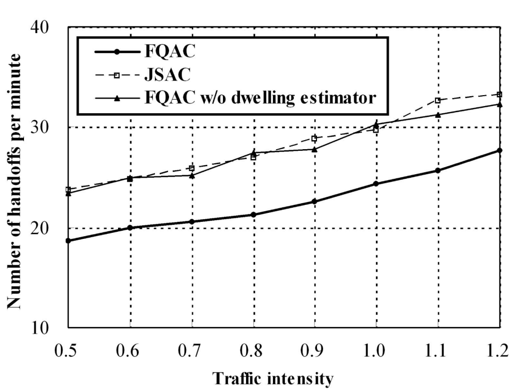

Fig. 8. Number of handoff per minute.

Acknowledgments

The authors would like to thank the anonymous reviewers for their comments to improve the presentation of the paper and Prof. Aura Ganz for handling the review process.

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