A QoS-Guaranteed Fuzzy Channel Allocation Controller for Hierarchical Cellular Systems

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***Abstract*—This paper proposes a *fuzzy channel allocation controller* (FCAC) for hierarchical cellular systems. The FCAC mainly contains a fuzzy channel allocation processor (FCAP) which is designed to be in a two-layer architecture that consists of a fuzzy admission threshold estimator in the first layer and a fuzzy channel allocator in the second layer. The FCAP chooses the handoff failure probability, defined as quality-of-service (QoS) index, and the resource availability as input linguistic variables for the fuzzy admission threshold estimator, where the Sugeno's position gradient-type reasoning method is applied to adaptively adjust the admission threshold for the fuzzy channel allocator. And the FCAP takes the mobility of user, the channel utilization, and the resource availability as input variables for the fuzzy channel allocator so that the channel allocation is finally determined, further based upon the admission threshold. Simulation results show that FCAC can always guarantee the QoS requirement of handoff failure probability for all traffic loads. Also it improves the system utilization by 31.2% while it increases the handoff rate by 12.9% over the overflow channel allocation (OCA) scheme [7]; it enhances the system utilization by 6% and still reduces the handoff rate by 6.7% as compared to the combined channel allocation (CCA) scheme [10], under a defined QoS constraint.**

I. INTRODUCTION

DUE to the increasing demands for wireless communication services, it is essential to reconfigure the existing cellular system into a hierarchical structure for enhancing system capacity and improving coverage. The hierarchical cellular system provides overlaid microcells for high-teletraffic area and overlaying macrocells for low-teletraffic region [1]–[5].

In such a hierarchical cellular system, Rappaport and Hu proposed an *overflow channel allocation* (OCA) scheme that allows a new or handoff call which has no channel available in the overlaid microcell to overflow to use free channel in the overlaying macrocell [6], [7]. The OCA scheme can reduce both the blocking probability of new calls and the forced termination probability of handoff calls, and it is easy to implement because no elaborate coordination between microcells is needed [6]–[8]. Beraldi *et al.* proposed a *reversible* hierarchical scheme [9], which allows the presence of handoff attempts from overlaying macrocell to overlaid microcell if there is idle channel available in the overlaid microcell. The reversible hierarchical scheme improves channel utilization in microcells and decreases blocking probabilities of both new call and handoff call since microcells are designed to be capable of supporting high capacity and balancing the traffic load.

We also proposed a *combined channel allocation* (CCA) mechanism for hierarchical cellular systems [10]. It combines overflow, underflow, and reversible schemes, where new or handoff calls having no idle channel to use in the overlaid microcell can *overflow* to use free channels in the overlaying macrocell, handoff calls from neighboring macrocell can *underflow* to use free channels in the overlaid microcell, and handoff attempts from macrocell-only region to a microcell in the same macrocell can be *reversed* to use free channels in the microcell. Simulation results showed that the CCA mechanism can attain better channel utilization by an amount of 23.7% but renders more handoff rate [11] by an amount of 19.8% than the OCA mechanism.

To guarantee QoS requirement for handoffs, these conventional techniques are to reserve a fixed number of guard channels or to provide a queue for handoffs [1], [12]. However, these methods are unable to cope with burstiness of traffic. In other words, though these protection schemes can even guarantee the QoS requirement of the handoff failure probability, the channel utilization would suffer from fundamental limitations by unpredictable statistical fluctuations within new and handoff calls. And they are difficult, if not impossible, to drive an accurate mathematical model to obtain the solution.

On the other hand, fuzzy logic control has growing success in various fields of applications, such as decision support, knowledge base systems, and pattern recognition. It is due to the inherent capability of fuzzy logic control to formalize control algorithms that can tolerate imprecision and uncertainty, emulating the cognitive processes that human beings use every day [13]–[15].

In addition, when applied to problems, fuzzy systems have often shown a faster and smoother response than conventional systems. It is thanks to the fact that fuzzy control rules are usually simpler and do not require great computational complexity. The latter aspect, along with the spread of very large scale integration (VLSI) hardware structure dedicated to fuzzy computation, makes fuzzy systems cost effective [16]. In the field of telecommunications, fuzzy systems are also beginning to be used in areas such as traffic control in ATM networks and channel allocation in mobile communication systems [17]–[20].

In this paper, we propose a QoS-guaranteed *fuzzy channel allocation controller* (FCAC) for hierarchical cellular systems. The FCAC contains a fuzzy channel allocation processor (FCAP), a resource estimator, a performance evaluator, and

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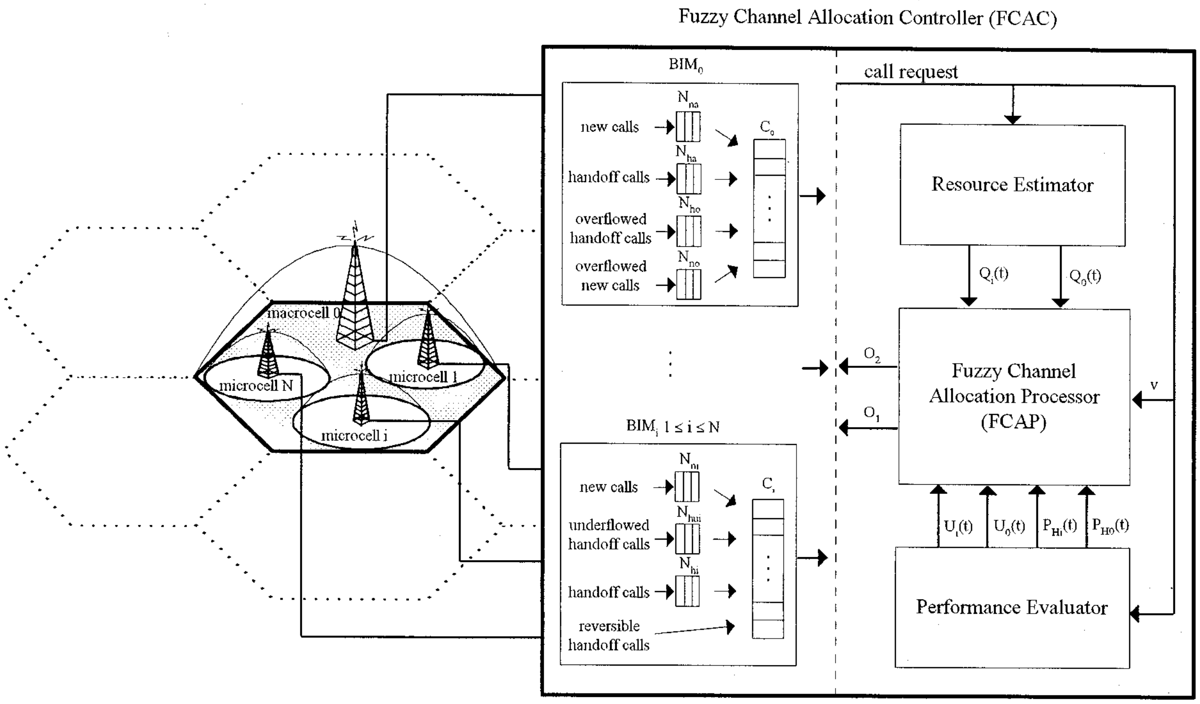

Fig. 1. The fuzzy channel allocation controller for hierarchical cellular systems.

base-station interface modules. It dynamically estimates available resources in macrocell and microcells, evaluates system performance, and determines whether and how to allocate resources to a call, based upon the call's QoS requirement, resource availability, and mobility. The FCAP is a two-layer fuzzy logic controller that contains the fuzzy admission threshold estimator in the first layer and the fuzzy channel allocator in the second layer. In the fuzzy admission threshold estimator, we apply the Sugeno's position-gradient type reasoning method to adaptively adjust the admission threshold for the fuzzy channel allocator. In the fuzzy channel allocator, we design to achieve utilization balancing between macrocell and microcells in order to obtain a higher channel utilization. The domain knowledge is based upon CCA mechanism we proposed in [10]. Simulation results show that FCAC can guarantee QoS requirement of existing calls; also, it achieves better system utilization by an amount of 31.2% but more handoff rate by an amount of 12.9% than OCA, and it attains more system utilization by 6% and still less handoff rate by 6.7% than CCA.

The rest of the paper is organized as follows. In Section II, functions of FCAC are described. Section III presents the design of FCAP. Section IV shows simulation results and discussions. Finally concluding remarks are given in Section V.

II. FUZZY CHANNEL ALLOCATION CONTROLLER (FCAC)

Fig. 1 shows the functional block diagram of the fuzzy channel allocation controller (FCAC) for hierarchical cellular systems, where the hierarchical cellular system contains a large geographical region tessellated by cells, referred to as macrocells, and each of which overlays several microcells. The overlaying macrocell is denoted by cell 0 and its overlaid microcells are denoted by cell $1, \cdots, N$. For cell i, a number of channels C_i is allocated, $0 \leq i \leq N$. FCAC contains functional blocks such as base-station interface module (BIM), performance evaluator, resource estimator, and fuzzy channel allocation processors (FCAP). It is installed in either a base station controller (BSC) or mobile switching center (MSC). Note that for simplicity, FCAC is drawn to do the channel allocation for one macrocell only. Functional blocks of FCAC are described as follows.

A. Base-Station Interface Modules (BIM)

BIM is to interface with the base station of macrocell or microcell. It provides complete partitioning buffers for queueing new and handoff calls which are originated in the corresponding cell and temporarily have no free channel to use. In the BIM for cell 0 (BIM_0), there is a new-call buffer with capacity N_{na} for new calls originating in the macrocell-only region, a handoff-call buffer with capacity N_{ha} for handoff calls from adjacent macrocells, an overflowed handoff-call buffer with capacity N_{ho} for overflowed handoff calls from overlaid microcells, and an overflowed new-call buffer with capacity N_{no} for overflowed new calls from overlaid microcells. In the BIM for cell i (BIM_i), $1 \leq i \leq N$, there is a new-call buffer with capacity N_{ni} for new call originations, an underflowed handoff-call buffer with capacity N_{hui} for underflowed handoff calls from the overlaying macrocell, and a handoff-call buffer with capacity N_{hi} for handoff calls from adjacent microcells. No buffer is provided for the reversible handoff calls. Reneging of new calls and dropping of handoff calls are considered because of new calls' impatience and handoff calls' moving out the handoff area.

Whenever BIM_i receives a call request, $0 \leq i \leq N$, it sends the necessary calling information to the resource estimator, the performance evaluator, and the FCAP. The calling information

TABLE I
CALCULATION OF AVAILABLE RESOURCE

k	Q_0	Q_i
1	$C_0 + N_{na} - r_0(t) - b_{na}(t)$	0
2	$C_0 + N_{ha} - r_0(t) - b_{ha}(t)$	0
3	$C_0 + N_{ho} - r_0(t) - b_{ho}(t)$	0
4	$C_0 + N_{no} - r_0(t) - b_{no}(t)$	$C_i + N_{ni} - r_i(t) - b_{ni}(t)$
5	$C_0 + N_{ha} - r_0(t) - b_{ha}(t)$	$C_i + N_{hui} - r_i(t) - b_{hui}(t)$
6	$C_0 + N_{ho} - r_0(t) - b_{ho}(t)$	$C_i + N_{hi} - r_i(t) - b_{hi}(t)$
7	$C_0 - r_0(t)$	$C_i - r_i(t)$

can distinctly indicate from which cell and in what type the call is originated. The k type of call is defined as: $k = 1$ denotes a new call originating in macrocell-only region; $k = 2$ denotes a handoff call from adjacent macrocell to macrocell-only region; $k = 3$ denotes a handoff call from microcell to macrocell-only region; $k = 4$ denotes new call originating in microcell; $k = 5$ denotes handoff call from adjacent macrocell to an overlaid microcell; $k = 6$ denotes handoff call from microcell to microcell; and $k = 7$ denotes reversible handoff. Note that the macrocell-only region is the area inside macrocell *0* but outside all microcells. The first three types of calls are to use channels in macrocell, while other types of calls can use channels either in macrocell or in microcell.

B. Resource Estimator

The resource estimator calculates the available resources in macrocell *0* and microcell i when it receives calling information of the type-k call from BIM_i at the time instant t, denoted by $Q_0(t)$ and $Q_i(t)$, respectively.

Since it knows system parameters of C_0, N_{na}, N_{ha}, N_{ho}, N_{no}, and C_i, N_{ni}, N_{hui}, N_{hi}, $1 \leq i \leq N$, it can obtain $Q_0(t)$ and $Q_i(t)$ by formulas shown in Table I.

In Table I, $r_0(t)$ ($r_i(t)$) is the number of occupied channels in C_0 (C_i) at time t; $b_{na}(t)$ ($b_{ha}(t)$, $b_{ho}(t)$, $b_{no}(t)$) is the number of waiting calls in the new-call buffer (handoff-call buffer, overflowed handoff-call buffer, overflowed new-call buffer) of BIM_0, at time t; and $b_{ni}(t)$ ($b_{hui}(t)$, $b_{hi}(t)$) is the number of waiting calls in the new-call buffer (underflowed handoff-call buffer, handoff-call buffer) of BIM_i, $1 \leq i \leq N$, at time t.

C. Performance Evaluator

The performance evaluator is to calculate the channel utilization and the handoff failure probability. The channel utilization of macrocell *0*(microcell i) at time t, denoted by $U_0(t)$ ($U_i(t)$), is defined as

$$U_0(t) = \frac{K_0(t)}{C_0} \left(U_i(t) = \frac{K_i(t)}{C_i} \right) \tag{1}$$

where $K_0(t)$ ($K_i(t)$) is the average number of busy channels in macrocell *0* (microcell i) at time t and C_0 (C_i) is the channel capacity for macrocell *0* (microcell i). In order to show the channel utilization balancing between macrocell and microcells, we further define a spatial averaging channel utilization of microcells at time t, denoted by $U_I(t)$, as

$$U_I(t) = \frac{\sum_{i=1}^{N} K_i(t)}{\sum_{i=1}^{N} C_i}. \tag{2}$$

Also we define the system utilization of the whole system at time t, denoted by $U(t)$, as

$$U(t) = \frac{K_0(t) + \sum_{i=1}^{N} K_i(t)}{C_0 + \sum_{i=1}^{N} C_i}. \tag{3}$$

The handoff failure probability in macrocell (microcells) at time t, denoted by $P_{H0}(t)$ ($P_{Hi}(t)$), is defined as

$$P_{H0}(t) = \frac{HB_0(t) + HR_0(t)}{NH_0(t)} \cdot \left(P_{Hi}(t) = \frac{HB_i(t) + HR_i(t)}{NH_i(t)} \right) \tag{4}$$

where

$HB_0(t)$ ($HB_i(t)$)	number of blocked waiting handoff calls in macrocell *0* (microcell i) at time t;
$HR_0(t)$ ($HR_i(t)$)	number of dropped handoff calls in macrocell *0* (microcell i) at time t; and
$NH_0(t)$ ($NH_i(t)$)	number of handoff calls in macrocell 0 (microcell i) at time t.

The handoff failure probability of the whole system at time t, denoted by $P_H(t)$, is given by

$$P_H(t) = \frac{\sum_{i=0}^{N} (HB_i(t) + HR_i(t))}{\sum_{i=0}^{N} NH_i(t)}. \tag{5}$$

D. Fuzzy Channel Allocation Processor (FCAP)

The FCAP performs the channel allocation using fuzzy logic control to attain high channel utilization and keep the QoS requirement guaranteed. Here, a threshold is designed for channel allocation, and it can be adaptively adjusted to cope with the input traffic fluctuation. The detailed design of an FCAP is described in the next section.

III. DESIGN OF FCAP

As Fig. 2 shows, an FCAP mainly consists of a fuzzy admission threshold estimator and a fuzzy channel allocator.

A. Fuzzy Admission Threshold Estimator

The fuzzy admission threshold estimator is to adaptively determine the decision thresholds for the fuzzy channel allocator

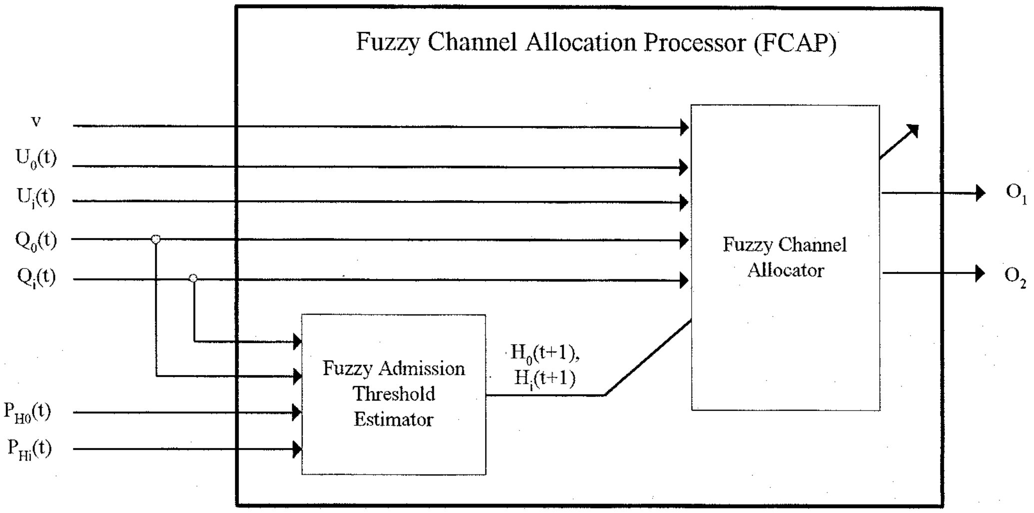

Fig. 2. The block diagram of fuzzy channel allocation processor.

so that the QoS requirement of handoff calls can be guaranteed and a high channel utilization can be achieved. The system QoS requirement is here defined as the maximum handoff failure probability which is denoted by P_H^*. The admission thresholds for macrocell *0* and microcell i during time period $(t, t+1]$, denoted by $H_0(t+1)$ and $H_i(t+1)$, are sent to the fuzzy channel allocator if a new call occurs in macrocell *0* or microcell i at time t. Note that "$t+1$" denotes the time instant the next new call arrives, and "1" denotes one unit of a new-call interarrival time.

We choose $P_{H0}(t)$ ($P_{Hi}(t)$) and $Q_0(t)$ ($Q_i(t)$) as input linguistic variables for the fuzzy admission threshold estimator to determine $H_0(t+1)$ ($H_i(t+1)$) for macrocell *0* (microcell i). Since the fuzzy rule set will be commonly used by macrocell *0* and microcell i, hereafter in this subsection we simply use $H(t+1)$, $P_H(t)$ and $Q(t)$, instead of $H_0(t+1)$ or $H_i(t+1)$, $P_{H0}(t)$ or $P_{Hi}(t)$, and $Q_0(t)$ or $Q_i(t)$.

Term sets for input variables are designed as $T(P_H(t)) = \{\text{Low, High}\} = \{L, H\}$, and $T(Q(t)) = \{\text{Enough, Not Enough}\} = \{E, NE\}$. And a function $g(x; x_0, x_1, a_0, a_1)$ defined below is chosen to be their membership function. It is a trapezoidal function given by

$$g(x; x_0, x_1, a_0, a_1) = \begin{cases} \dfrac{x-x_0}{a_0}+1, & \text{for } x_0-a_0 < x \le x_0 \\ 1, & \text{for } x_0 < x \le x_1 \\ \dfrac{x_1-x}{a_1}+1, & \text{for } x_1 < x \le x_1+a_1 \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $x_0(x_1)$ is the left (right) edge of the trapezoidal function; a_0 (a_1) is the left (right) width of the trapezoidal function.

Denote $\mu_L(P_H(t))$ and $\mu_H(P_H(t))$ to be the membership functions for L and H in $T(P_H(t))$, respectively, and define $\mu_L(P_H(t))$ and $\mu_H(P_H(t))$ as

$$\mu_L(P_H(t)) = g(P_H(t); 0, L_e, 0, L_w) \tag{7}$$

$$\mu_H(P_H(t)) = g(P_H(t); H_e, 1, H_w, 0). \tag{8}$$

H_e would be set to be P_H^*, L_w and H_w could be the safety margin provided to tolerate the dynamic behavior of handoff failure probability and guarantee the QoS requirement, and the edge L_e is $L_e = H_e - L_w$.

Similarly, let $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ be the membership functions for E and NE in $T(Q(t))$, respectively, and define $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ as

$$\mu_E(Q(t)) = g(Q(t); E_e, R_e, E_w, 0) \tag{9}$$

$$\mu_{NE}(Q(t)) = g(Q(t); 0, R_n, 0, NE_w). \tag{10}$$

The maximum possible "enough" value of available resource R_e would be the sum of buffer size and allocation channels, E_e would be a safety margin of available resource, R_n would be set to be a fraction of available resource, and E_w and NE_w are provided to tolerate the change of traffic.

Based on chosen input variables and their terms, the fuzzy admission threshold estimator has $M = 4$ fuzzy IF–THEN rules. The fuzzy rules have the following form:

Rule m: IF $P_H(t)$ is X_{1m} and $Q(t)$ is X_{2m},
THEN $h_m(t+1)$

where X_{im} is the term of the ith linguistic variable used in rule m, and $h_m(t+1)$ is the output function of rule m for the time period $(t, t+1]$, $1 \le m \le M$.

Here, we apply the Sugeno's position-gradient type reasoning method [21], [22] to effectively derive $h_m(t+1)$ and then to obtain $H(t+1)$. The inference in the Sugeno's method has a built-in defuzzification such that $h_m(t+1)$ can be expressed as

$$h_m(t+1) = \beta \cdot H(t) + a_m(t+1) \tag{11}$$

where

β, $0 < \beta < 1$,	forgetting constant that can maintain the estimator stability,
$H(t)$	admission threshold during last time period $(t-1, t]$, and
$a_m(t+1)$	adjustment parameter for $h_m(t+1)$.

Then $H(t+1)$ is given by

$$\begin{aligned} H(t+1) &= \sum_{m=1}^{M} h_m(t+1) w_m(t+1) \\ &= \beta \cdot H(t) + \sum_{m=1}^{M} a_m(t+1) w_m(t+1) \end{aligned} \tag{12}$$

where $w_m(t+1)$ is the weighting factor for the output variable of rule m, defined as $w_m(t+1) = \mu_{X_{1m}}(P_H(t)) \cdot \mu_{X_{2m}}(Q(t))$. Since membership functions are set to be symmetrical, $\sum_{m=1}^{M} w_m(t+1) = 1$.

The adjustment parameter $a_m(t+1)$ is obtained by the gradient decent method, where an error function at time t is defined as

$$E(t) = \tfrac{1}{2}\left(P_H(t) - P_H^*\right)^2. \tag{13}$$

Note that $E(t)$ is given in the sense that $P_H(t)$ needs to be controlled around P_H^*. Then $a_m(t+1)$ is given by

$$\begin{aligned} a_m(t+1) &= a_m(t) - \eta \cdot \frac{\partial E(t)}{\partial a_m(t)} \\ &= a_m(t) - \eta \cdot (P_H(t) - P_H^*) \cdot \frac{\partial P_H(t)}{\partial a_m(t)}. \end{aligned} \tag{14}$$

where η is an adaptation gain which must be properly chosen.

Because the admission threshold $H(t+1)$ could be regarded as an entry barrier to regulate new calls coming to the system, and the change of $P_H(t+1)$ during $(t, t+1]$, denoted by $\Delta P_H(t+1)$ would be varied in accordance with $H(t+1)$ so that $P_H(t+1)$ can be kept at around P_H^* to fulfill QoS requirement, we heuristically make an approximation that $\Delta P_H(t+1)$ has a first-order relationship with $H(t+1)$. Then $P_H(t+1)$ can be expressed as

$$\begin{aligned} P_H(t+1) &= P_H(t) + \Delta P_H(t+1) \\ &\approx P_H(t) - \sigma \cdot H(t+1) + c \end{aligned} \tag{15}$$

where σ is an experience value and c is a constant value. For example, $\Delta P_H(t+1) \approx -0.2\% \cdot H(t+1) + 0.1\%$ means that $\Delta P_H(t+1)$ in the range of $[0.1\%, -0.1\%]$ is inversely varied with respect to $H(t+1)$ in the range of [0, 1]. Since $\Delta P_H(t+1)$ is designed to change gradually at a rate of $0.1 \cdot P_H^*$, the value of σ could be chosen to be 0.002. However, in order to attain a better adjustment of $H(t+1)$ to fulfill QoS requirement in acute traffic fluctuation, we further set σ to be dynamically changed according to the number of handoff calls during $(t, t+1]$. In our example, it is frequent that only few handoffs occur during $(t, t+1]$, thus σ is set to be $(NH(t, t+1]/1000)$, where $NH(t, t+1]$ is the number of handoff calls during $(t, t+1]$. Equation (15) can be rewritten as

$$\left(1 - z^{-1}\right) \frac{\partial P_H(t)}{\partial a_m(t)} \approx -\sigma \cdot \frac{\partial H(t)}{\partial a_m(t)} \tag{16}$$

where z^{-1} denotes one unit of a new-call interarrival time. And then we have an expression for $(\partial P_H(t)/\partial a_m(t))$ as

$$\frac{\partial P_H(t)}{\partial a_m(t)} \approx \gamma \frac{\partial P_H(t-1)}{\partial a_m(t-1)} - \sigma \cdot \frac{\partial H(t)}{\partial a_m(t)} \tag{17}$$

where γ is a pole which is set to a value very close to but less than one to avoid infinite memory and marginal stability of this gradient evolution.

Finally, we rewrite (11) as

$$\left(1 - \beta z^{-1}\right) \frac{\partial H(t)}{\partial a_m(t)} = w_m(t) \tag{18}$$

and we obtain $(\partial H(t)/\partial a_m(t))$ by

$$\frac{\partial H(t)}{\partial a_m(t)} = \beta \frac{\partial H(t-1)}{\partial a_m(t-1)} + w_m(t). \tag{19}$$

B. Fuzzy Channel Allocator

We choose five input linguistic variables for fuzzy channel allocator: the channel utilization in macrocell 0 ($U_0(t)$), the channel utilization in microcell i ($U_i(t)$), the available resource in macrocell *0* ($Q_0(t)$), the available resource in microcell i ($Q_i(t)$), and the mobile speed (v). $U_0(t)$ and $U_i(t)$ can show the traffic load intensity and the load balancing among cells; $Q_0(t)$ and $Q_i(t)$ can implicate the remaining capacity; and v can show the handoff rate. The term set for both $U_0(t)$ and $U_i(t)$ is defined as $T(U_0(t)) = T(U_i(t)) = \{\text{Low, High}\} = \{L, H\}$, the term set for both $Q_0(t)$ and $Q_i(t)$ is $T(Q_0(t)) = T(Q_i(t)) = \{\text{Enough, Not Enough}\} = \{E, NE\}$, and the term set for v is $T(v) = \{\text{Slow, Fast}\} = \{S, F\}$. Let $\mu_L(U_0(t))$ ($\mu_L(U_i(t))$) and $\mu_H(U_0(t))$ ($\mu_H(U_i(t))$) denote the membership functions of terms L and H in $T(U_0(t))$ ($T(U_i(t))$), respectively, and let $\mu_L(U_0(t))$, $\mu_H(U_0(t))$, $\mu_L(U_i(t))$, and $\mu_H(U_i(t))$ be

$$\mu_L(U_0(t)) = g(U_0(t); 0, L_e, 0, L_w) \tag{20}$$

$$\mu_H(U_0(t)) = g(U_0(t); 1, 1, H_w, 0) \tag{21}$$

$$\mu_L(U_i(t)) = g(U_i(t); 0, L_e, 0, L_w) \tag{22}$$

$$\mu_H(U_i(t)) = g(U_i(t); 1, 1, H_w, 0). \tag{23}$$

Here L_e would be a fraction of channel utilization, and L_w and H_w would be a change rate of channel utilization provided to tolerate the dynamic behavior of $U_0(t)$ and $U_i(t)$, respectively. The membership functions for terms of E and NE of $Q_0(t)$ and $Q_i(t)$ have the same definition as in (9) and (10). The speed of the mobile user is hard to obtain. Usually the velocity of a mobile station can be estimated by the global positioning system (GPS), the Doppler effect, the elapsed time in a cell, the propagation time of the signal, and the number of level crossings of the average signal level [23]. The membership functions for terms S and F in v, denoted by $\mu_S(v)$ and $\mu_F(v)$, are given by

$$\mu_S(v) = g(v; 0, S_e, 0, S_w) \tag{24}$$

$$\mu_F(v) = g(v; F_e, F_h, F_w, 0) \tag{25}$$

where

S_e (F_e)	would be a fraction of slow (fast) speed of mobile user,
S_w (F_w)	is provided to tolerate the change of slow (fast) speed, and
F_h	would be the fastest speed.

There are two output variables, O_1 and O_2, in the fuzzy channel allocator. The output variable O_1 represents whether the call is accepted or rejected, and O_2 indicates with which channel in either macrocell or microcell the call is allocated. In order to provide a soft channel allocation decision, not only "accept" and "reject" but also "weak accept" and "weak reject" are employed to describe the allocation decision. Thus, the term set for the output linguistic variable O_1 is defined as $T(O_1) = \{\text{Accept } (A), \text{ Weak Accept } (WA), \text{ Weak Reject } (WR), \text{ Reject } (R)\}$, and the term set for O_2 is defined as , $T(O_2) = \{\text{Macrocell } (M_a), \text{ Microcell } (M_i)\}$.

We further define a delta function, $\delta(x-x_0)$, for the membership functions of the output linguistic variables, where $\delta(x-x_0)$ is characterized as $\int_{-\infty}^{\infty} \delta(x-x_0)\,dx = 1$ and $\delta(x-x_0) = \infty$, $x = x_0$; $\delta(x-x_0) = 0$, $x \neq x_0$. The membership functions for terms A, WA, WR, and R in $T(O_1)$, denoted by μ_A, μ_{WA}, μ_{WR}, and μ_R, respectively, are given by

$$\mu_A = \delta\left(O_1 - A_c\right) \tag{26}$$

$$\mu_{WA} = \delta\left(O_1 - WA_c\right) \tag{27}$$

$$\mu_{WR} = \delta\left(O_1 - WR_c\right) \tag{28}$$

$$\mu_R = \delta\left(O_1 - R_c\right). \tag{29}$$

Without loss of generality, we set $R_c = 0$, $A_c = 1$, and let $WR_c = (R_c + H(t+1))/2$, $WA_c = (A_c + H(t+1))/2$. A call can be allocated with channel if O_1 is greater than the admission threshold $H(t+1)$. And the membership functions for terms M_a and M_i in $T(O_2)$, denoted by μ_{M_i} and μ_{M_a}, respectively, are given by

$$\mu_{M_a} = \delta\left(O_2 - M_{ac}\right) \tag{30}$$

$$\mu_{M_i} = \delta\left(O_2 - M_{ic}\right). \tag{31}$$

M_{ac} and M_{ic} are set to be positive one and negative one, respectively. If O_2 is greater than zero, the call is allocated with a macrocell channel, otherwise, with a microcell channel.

There are different call types in hierarchical cellular systems. For calls that can use only macrocell's channel, only input linguistic variables of $U_0(t)$ and $Q_0(t)$ are enabled. For calls that could use channels in either macrocell or microcell, input linguistic variables of $U_0(t)$, $U_i(t)$, $Q_0(t)$, $Q_i(t)$, and v are enabled. The fuzzy rule base with dimension $|T(U_0(t))| \times |T(Q_0(t))|$ is shown in Table II for the former, and that with dimension $|T(v)| \times |T(U_0(t))| \times |T(U_i(t))| \times |T(Q_0(t))| \times |T(Q_i(t))|$ is shown in Table III for the latter, where $|T(\cdot)|$ denotes the number of terms in $T(\cdot)$.

The general idea of designing the fuzzy rules listed in Tables II and III is described as follows. If the available resource in either macrocell or microcell is enough, a call would have a chance of entering the system, and *vice versa*; if the available resource is enough in macrocell but not enough in microcell, the macrocell channel would be preferred, and *vice versa*; we choose a cell with low channel utilization, instead of the one with high utilization, for balancing traffic load if the available resource in both macrocell and microcell has same fuzzy terms in the premises of the fuzzy rule; and we also allocate calls to be biased toward macrocell if the speed is fast for lessening frequent handoff, and *vice versa*.

TABLE II
INFERENCE RULES FOR MACROCELL ONLY REGION

k	Q_0	Q_i
1	$C_0 + N_{na} - r_0(t) - b_{na}(t)$	0
2	$C_0 + N_{ha} - r_0(t) - b_{ha}(t)$	0
3	$C_0 + N_{ho} - r_0(t) - b_{ho}(t)$	0
4	$C_0 + N_{no} - r_0(t) - b_{no}(t)$	$C_i + N_{ni} - r_i(t) - b_{ni}(t)$
5	$C_0 + N_{ha} - r_0(t) - b_{ha}(t)$	$C_i + N_{hui} - r_i(t) - b_{hui}(t)$
6	$C_0 + N_{ho} - r_0(t) - b_{ho}(t)$	$C_i + N_{hi} - r_i(t) - b_{hi}(t)$
7	$C_0 - r_0(t)$	$C_i - r_i(t)$

The *max–min* inference method is adopted. It first applies the *min* operator on membership values of the terms of all input linguistic variable for each rule. Assume that a call is originated in microcell i and the inference rules in Table III are applied. We denote the minimal result for rule i to be m_i, $1 \leq i \leq 32$, and obtain m_{16}, for example, by

$$\begin{aligned} m_{16} = \min\big(&\mu_F(v),\, \mu_L\left(U_0(t)\right),\, \mu_L\left(U_i(t)\right),\, \mu_{NE}\left(Q_0(t)\right), \\ &\mu_{NE}\left(Q_i(t)\right)\big). \end{aligned} \tag{32}$$

Then the method applies the *max* operator to yield the overall membership value. For the output variable O_1, there are four rules for term R in Table III, which are rules 4, 8, 20, 28. Then the overall membership value for the term R, denoted by m_R, is given by

$$m_R = \max\left(m_4,\, m_8,\, m_{20},\, m_{28}\right). \tag{33}$$

Similarly, m_A, m_{WA} and m_{WR} are yielded as

$$\begin{aligned} m_A = \max\big(&m_1,\, m_2,\, m_5,\, m_6,\, m_9,\, m_{10},\, m_{13},\, m_{14},\, m_{17} \\ &m_{19},\, m_{21},\, m_{23},\, m_{25},\, m_{27},\, m_{29},\, m_{31}\big) \end{aligned} \tag{34}$$

$$m_{WA} = \max\left(m_3,\, m_7,\, m_{11},\, m_{15},\, m_{18},\, m_{22},\, m_{26},\, m_{30}\right) \tag{35}$$

$$m_{WR} = \max\left(m_{12},\, m_{16},\, m_{24},\, m_{32}\right). \tag{36}$$

Afterwards, we use the *center-of-area* defuzzification method to derive the defuzzification value. The defuzzification value, denoted by $\tilde{O}_1$, is given as shown in (37) at the bottom of the page. Then the output variable O_1 is obtained by

$$O_1 = \begin{cases} 0, & \text{for } \tilde{O}_1 \geq H(t+1) \\ 1, & \text{for } \tilde{O}_1 < H(t+1). \end{cases} \tag{38}$$

$$\tilde{O}_1 = \frac{m_A \times A_c + m_{WA} \times WA_c + m_{WR} \times WR_c + m_R \times R_c}{m_A + m_{WA} + m_{WR} + m_R}. \tag{37}$$

TABLE III
INFERENCE RULES FOR OVERLAY REGION

Rule	IF					THEN		Rule	IF					THEN	
	v	$U_0(t)$	$U_i(t)$	$Q_0(t)$	$Q_i(t)$	O_1	O_2		v	$U_0(t)$	$U_i(t)$	$Q_0(t)$	$Q_i(t)$	O_1	O_2
1	F	H	H	E	E	A	M_a	17	S	H	H	E	E	A	M_i
2	F	H	H	E	NE	A	M_a	18	S	H	H	E	NE	WA	M_a
3	F	H	H	NE	E	WA	M_i	19	S	H	H	NE	E	A	M_i
4	F	H	H	NE	NE	R	M_a	20	S	H	H	NE	NE	R	M_i
5	F	H	L	E	E	A	M_i	21	S	H	L	E	E	A	M_i
6	F	H	L	E	NE	A	M_a	22	S	H	L	E	NE	WA	M_a
7	F	H	L	NE	E	WA	M_i	23	S	H	L	NE	E	A	M_i
8	F	H	L	NE	NE	R	M_i	24	S	H	L	NE	NE	WR	M_i
9	F	L	H	E	E	A	M_a	25	S	L	H	E	E	A	M_a
10	F	L	H	E	NE	A	M_a	26	S	L	H	E	NE	WA	M_a
11	F	L	H	NE	E	WA	M_i	27	S	L	H	NE	E	A	M_i
12	F	L	H	NE	NE	WR	M_a	28	S	L	H	NE	NE	R	M_a
13	F	L	L	E	E	A	M_a	29	S	L	L	E	E	A	M_i
14	F	L	L	E	NE	A	M_a	30	S	L	L	E	NE	WA	M_a
15	F	L	L	NE	E	WA	M_i	31	S	L	L	NE	E	A	M_i
16	F	L	L	NE	NE	WR	M_a	32	S	L	L	NE	NE	WR	M_i

Note that $H(t+1) = H_0(t+1)$ if the call is a new call and is originated in macrocell-only region, and $H(t+1) = \min(H_0(t+1), H_i(t+1))$ if the call is a new call and is originated in microcell i. On the other hand, in order to give a good protection for handoff calls, $H(t+1) = 0$ if the call is a handoff.

We similarly adopt the *max–min* inference method and apply the *center-of-area* defuzzification method for output variable O_2, not further described here.

IV. SIMULATION RESULTS AND DISCUSSIONS

In the simulations, a hierarchical cellular system with $N = 9$ microcells constructed along the Manhattan streets is assumed, and the handoff behavior of users is characterized by a teletraffic flow matrix [4], defined as shown in the equation at the bottom of the page where a_{ij}, $i \neq j$, represents the probability of a handoff call originated in cell i and directed to cell j, $1 \leq j \leq N$, and a_{id} denotes the probability of this handoff call directed to the adjacent macrocell. $\sum_{j=0} a_{ij} = 1$ for $0 \leq i \leq N$, and a_{ii} would be zero.

The number of mobile stations in each cell is assumed to be 550, and the new-call arrival process follows a Poisson process with calling rate per mobile station (user) λ. We assume that low- and high-mobility users are generated in a ratio of 7 : 3, and the cell dwell time is exponentially distributed with mean 180 s (18 s) for the high-mobility users in macrocell (microcells) and

---

$$
A = \begin{bmatrix}
a_{00} & a_{01} & a_{02} & \cdots & a_{0N} & a_{0d} \\
a_{10} & a_{11} & a_{12} & \cdots & a_{1N} & a_{1d} \\
a_{20} & a_{21} & a_{22} & \cdots & a_{2N} & a_{2d} \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
a_{N0} & a_{N1} & a_{N2} & \cdots & a_{NN} & a_{Nd}
\end{bmatrix}
= \begin{bmatrix}
0.0 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 \\
0.1 & 0.0 & 0.3 & 0.0 & 0.3 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.3 \\
0.1 & 0.2 & 0.0 & 0.2 & 0.0 & 0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.3 \\
0.1 & 0.0 & 0.3 & 0.0 & 0.0 & 0.0 & 0.3 & 0.0 & 0.0 & 0.0 & 0.3 \\
0.1 & 0.2 & 0.0 & 0.0 & 0.0 & 0.2 & 0.0 & 0.2 & 0.0 & 0.0 & 0.3 \\
0.0 & 0.0 & 0.25 & 0.0 & 0.25 & 0.0 & 0.25 & 0.0 & 0.25 & 0.0 & 0.0 \\
0.1 & 0.0 & 0.0 & 0.2 & 0.0 & 0.2 & 0.0 & 0.0 & 0.0 & 0.2 & 0.3 \\
0.1 & 0.0 & 0.0 & 0.0 & 0.3 & 0.0 & 0.0 & 0.0 & 0.3 & 0.0 & 0.3 \\
0.1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & 0.0 & 0.2 & 0.0 & 0.2 & 0.3 \\
0.1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.3 & 0.0 & 0.3 & 0.0 & 0.3
\end{bmatrix}
$$

with 1440 s (144 s) for low-mobility users in macrocell (microcells). And the speed of mobile users is assumed to be uniformly distributed in the range of 0–40 km (40–80 km) for low- (high-) mobility users. We also assume that the mean unencumbered session duration is 100 s and the patience (dwell) time for queued new (handoff) calls is in the range of 5–20 s. There are 150 channels fixedly allocated to macrocell and microcells with a pattern of $(C_0, C_1, \ldots, C_N) = (42, 12, \ldots, 12)$. If the OCA and CCA schemes are applied, the system reserves a number of channels C_{ri} as guard channels for handoff calls in cell i, $0 \leq i \leq N$, which are denoted by $(C_{r0}, C_{r1}, \ldots, C_{rN})$. We do some simulations and obtain the appropriate $(C_{r0}, C_{r1}, \ldots, C_{rN}) = (8, 4, \ldots, 4)$ for OCA scheme and $(C_{r0}, C_{r1}, \ldots, C_{rN}) = (3, 2, \ldots, 2)$ for CCA schemes at $\lambda = 5 \times 10^{-4}$. Since the reneging (dropping) process is considered, it is not necessary to provide a large buffer size for new and handoff calls [10]; all buffer sizes in macrocell and microcells are assumed to be 3. Note that in the following performance comparisons, an OCA scheme provides no buffer and the CCA scheme supports the same buffering scheme and capacity as FCAC does.

Based upon the QoS requirement and the knowledge of the CCA mechanism, parameters of membership functions for input linguistic variables in the fuzzy admission threshold estimator are selected as follows: $L_e = 0.01$, $H_e = 0.02$, and $L_w = H_w = 0.01$ for $\mu_L(P_H(t))$ and $\mu_H(P_H(t))$ in (7) and (8); $E_e = E_w = NE_w = 17$, $R_e = 45$, and $R_n = 0$ for $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ with macrocell in (9) and (10); $E_e = E_w = NE_w = 7$, $R_e = 15$, and $R_n = 0$ for $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ with microcells in (9) and (10). In the fuzzy channel allocator, parameters of membership functions for input linguistic variables are selected as follows: $L_e = L_w = H_w = 0.5$ for $\mu_L(U_0(t))$, $\mu_H(U_0(t))$, $\mu_L(U_i(t))$, and $\mu_H(U_i(t))$ in (20)–(23); $E_e = E_w = NE_w = 17$, $R_e = 45$, and $R_n = 0$ for $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ with macrocell in (9) and (10); $E_e = E_w = NE_w = 7$, $R_e = 15$, and $R_n = 0$ for $\mu_E(Q(t))$ and $\mu_{NE}(Q(t))$ with microcells in (9) and (10); and $S_w = F_w = 40$ km, $S_e = 20$ km, $F_e = 60$ km, and $F_h = 80$ km for $\mu_S(v))$ and $\mu_L(v)$ in (24) and (25). And constant parameters are set to be $\eta = 0.01$ and $\beta = \gamma = 0.9$.

Three more performance measures such as the new-call failure probability, the forced termination probability, and the handoff rate are concerned, in addition to $U(t)$ and $P_H(t)$. The new-call failure probability at time t, denoted by $P_N(t)$, is defined as

$$P_N(t) = \frac{\sum_{i=0}^{N} (NB_i(t) + NR_i(t))}{\sum_{i=0}^{N} NN_i(t)} \tag{39}$$

where $NB_i(t)$ $(NR_i(t))$ is the number of blocked (reneging) new calls in cell i and $NN_i(t)$ $(NN_0(t))$ is the number of new calls originating in microcell i (macrocell-only region), at time t. Forced termination of a call occurs if a call is corrupted due to a handoff failure during its conversation time. The forced termination probability at time t, denoted by $P_F(t)$, is defined as

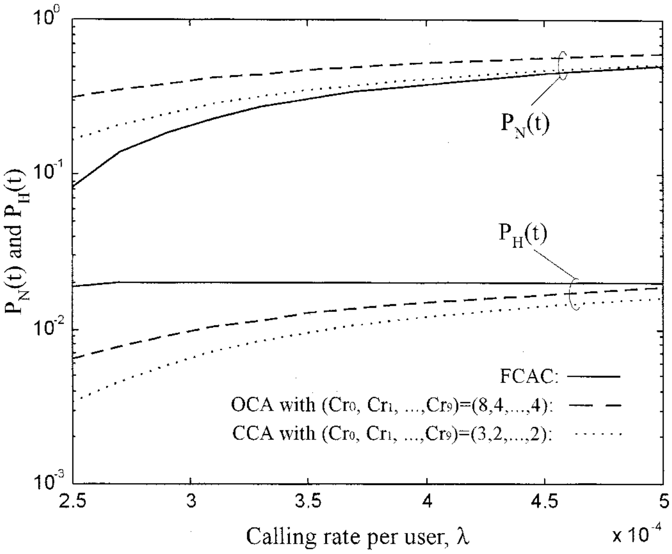

Fig. 3. $P_H(t)$ and $P_N(t)$ for FCAC, OCA, and CCA schemes.

$$P_F(t) = \frac{\sum_{i=0}^{N} (HB_i(t) + HR_i(t))}{\sum_{i=0}^{N} NS_i(t)} \tag{40}$$

where $HB_i(t)$ $(HR_i(t))$ is the number of blocked (dropped) handoff calls in cell i and $NS_i(t)$ is the number of admitted new calls originated in cell i, at time t. The handoff rate at time t, denoted by $R_H(t)$, is defined as

$$R_H(t) = \frac{\sum_{i=0}^{N} NH_i(t)}{\sum_{i=0}^{N} NS_i(t)}. \tag{41}$$

Fig. 3 shows the new-call failure probability $P_N(t)$ and the handoff failure probability $P_H(t)$ for schemes of FCAC, OCA, and CCA versus the calling rate per user λ at time $t = 10^8$. It can be seen that, as λ varies, $P_H(t)$ of FCAC remains constant at around $P_H^* = 2\%$, denoting the system QoS is guaranteed, and $P_N(t)$ is minimized so as to maximize the system capacity, comparing with OCA and CCA. It is because FCAC uses fuzzy logic control and considers more system information than conventional schemes to allocate channels. Fuzzy logic is a soft logic as the truth value of an entity, not restricted to either false or true, but in a continuum of [0, 1]. And softness of truth value is more appropriate to represent in determining if a given requirement constraint is complied with or violated. This in effect removes the imposition of worse case assumption from the decision making of channel allocation. It is also because the fuzzy admission threshold estimator adopts the Sugeno's position gradient-type reasoning method to effectively estimate the

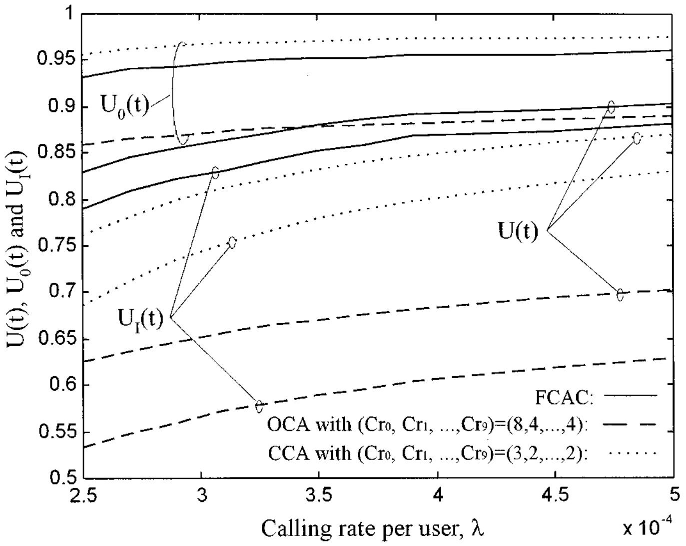

Fig. 4. $U(t), U_0(t)$, and $U_I(t)$ for FCAC, OCA, and CCA schemes.

optimal admission threshold contained in each rule from its observed information; and the fuzzy channel allocator appropriately controls the admission of calls according to fuzzy admission threshold value and allocates channels in either microcell or macrocell. While the conventional policies are inadaptive to determine the number of guard channels to maintain, but not to overprotect, the QoS requirement as the traffic load is fluctuating and the changing λ is unpredictable.

Fig. 4 shows the overall system utilization $U(t)$, the channel utilization in macrocell $U_0(t)$ and in microcell $U_I(t)$ versus the calling rate per user λ for schemes of FCAC, OCA, and CCA at time $t = 10^8$. It reveals that $U(t)$ of FCAC gains 31.2% and 6% improvement over the OCA and CCA methods, respectively; $U_0(t)$ of FCAC is increased by an amount of 8.4% over OCA but is decreased by 2.1% under CCA, while $U_I(t)$ of FCAC outperforms OCA and CCA by a significant amount of 44.6% and 10%, respectively; and the pair of $U_0(t)$ and $U_I(t)$ for FCAC is the closest one among those for OCA and CCA schemes. The latter two phenomena justify that FCAC can achieve the highest system utilization for more balancing utilization among cells than conventional schemes. And it is because fuzzy logic is a powerful tool that allows us to qualitatively represent control rules naturally, on the basis of a simple linguistic description, to overcome some uncertainty and imprecision.

Fig. 5 shows the forced termination probability $P_F(t)$ versus the calling rate per user λ for schemes of FCAC, OCA, and CCA at time $t = 10^8$. It is found that $P_F(t)$ of FCAC has flat curve around at 2%. This is because we have obtained the unchanged $P_H(t)$, shown in Fig. 3.

Fig. 6 shows the handoff rate versus the calling rate per user λ for schemes of FCAC, OCA, and CCA at time $t = 10^8$. It reveals that FCAC has more handoff rate by an amount of 12.9% than OCA. The reason is that the design of FCAC is based on the knowledge of CCA which combines overflow, reversible, and underflow. However, the signaling overheads for these handoffs might not cost as much as those for conventional handoffs between macrocells since most of these handoffs occurred in the same macrocell. And FCAC achieves a lesser handoff rate than CCA. It is not only because of more information such as the speed of mobile station considered in FCAC but also because of the fuzzy logic control that can provide decision support and expert system with powerful reasoning capability.

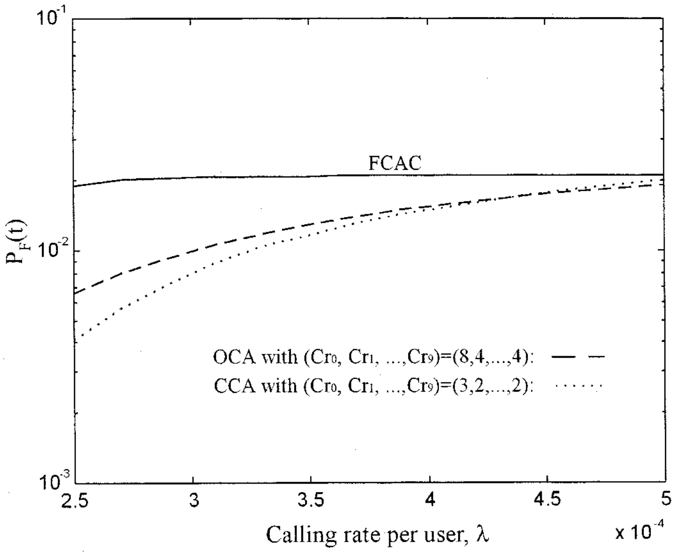

Fig. 5. $P_F(t)$ for FCAC, OCA, and CCA schemes.

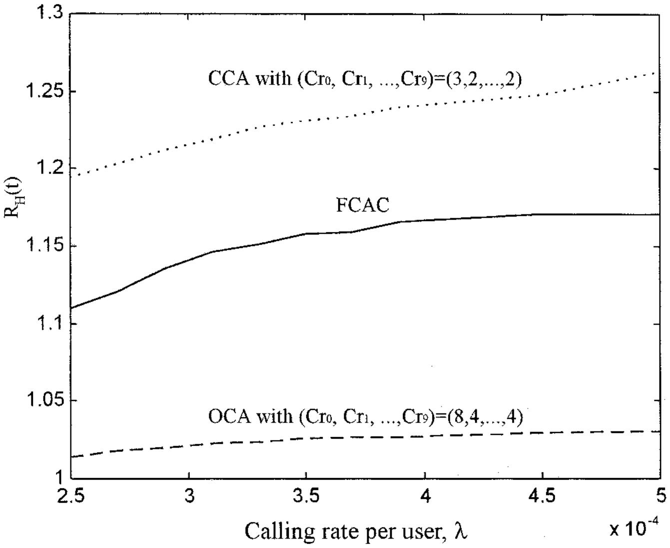

Fig. 6. $R_H(t)$ for FCAC, OCA, and CCA schemes.

V. CONCLUDING REMARKS

In this paper, we propose a QoS-guaranteed FCAC for hierarchical cellular systems. The FCAC is designed to be a two-layer controller which consists of a fuzzy admission threshold estimator in the first layer and a fuzzy channel allocator in the second layer. The fuzzy admission threshold estimator applies the Sugeno's position-gradient type reasoning method to adaptively adjust the admission threshold value so that the QoS constraint can be kept. The fuzzy channel allocator uses soft logic to determine whether a call is accepted or not and which channel in macrocell or microcell will be allocated. Simulation results show that the proposed FCAC improves the overall channel utilization 31.2% higher than the OCA scheme and 6% better than the CCA scheme, while maintaining the QoS requirement; and it still reduces the handoff rate by an amount of 6.7% under the CCA mechanism but increases the handoff rate by an amount of 12.9% over the OCA mechanism. Since most of the handoffs mentioned here are within the same macrocell, the signaling overheads for these handoffs are not as much as those needed in handoffs between macrocells. The FCAC would be a promising and feasible approach.

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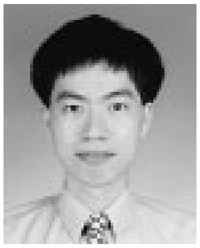

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