

schemes are proposed, but QoS requirements in terms of outage probability cannot always be satisfied.

To address technical challenges in CAC for wireless communications, in this paper, we investigate CAC for a wideband CDMA cellular system using the fuzzy logic approach and based on real-time measurements, without making simplified assumptions on user mobility and teletraffic models. Traditionally, a CAC scheme should explore a set of measured parameters to make the decision of accepting or rejecting a requesting call. This type of control scheme makes little or no allowance for measurement uncertainties [14]. However, in the wireless system, due to user mobility and varying channel conditions, the measurements obtained are, in general, not accurate. Furthermore, it is also difficult to obtain the complete statistics of input traffic. As a result, the decision has to be based on the imprecision and uncertain measurements. To this end, fuzzy logic provides an approximate but effective means of describing the behavior of the systems that are too complex and not easy to tackle mathematically [15]. It is an extension of Boolean logic in the sense that it also provides a platform for handling uncertainty and imprecise knowledge. Having the nature of coping with uncertainty and imprecision problems, fuzzy logic is expected to provide a good solution to the development of a call admission control scheme.

The fuzzy CAC scheme proposed here takes into account the MS mobility information, multimedia traffic characteristics, QoS provisioning, and system resource utilization. The user mobility information is obtained via signal power measurements, without using a predetermined or simplified model. Both intracell and intercell effective bandwidths are used to determine the resource requirement of each call. When an MS requests for service, first the fuzzy CAC scheme estimates its effective bandwidths in the target cell and the neighboring cells and its mobility information, which facilitate the CAC decision and resource reservation for the call if admitted. Then, the fuzzy CAC scheme makes a decision to accept the call only if the QoS requirements of all the on-going calls in the target cell and the neighboring cells can be guaranteed and the QoS requirement of the new call can be ensured. Simulation results are presented to demonstrate that the fuzzy CAC scheme can achieve low new call blocking and handoff call dropping probabilities, satisfy the outage probability requirement, and make efficient use of system resources. The rest of the paper is organized as follows: Section 2 describes the system model. Section 3 defines the intracell and intercell effective bandwidths based on [3]. Section 4 is devoted to the design of the fuzzy CAC scheme. Numerical results are presented in Section 5 and conclusions are given in Section 6.

2 SYSTEM MODEL

We consider a wideband CDMA cellular system with hexagonal cells of equal size. Each cell contains a centrally located base station (BS) with an omnidirectional antenna. The same radio spectrum is reused in every cell. The MSs communicate with their home BSs via the air interface, and a number of BSs are connected to a mobile switching center (MSC) which is in turn connected to a backbone wireline network. Separate frequency bands are used for the forward and reverse links, so that each BS experiences interference only from the MSs. The focus is placed on the CAC process for the reverse link.

Fig. 1. The hexagonal cell layout.

In the forward link, each BS broadcasts a unique pilot signal to the MSs. The pilot signals from different BSs are distinguished by different scrambling codes. The MS can detect the pilot signal from any BS when the strength of the pilot signal is above a certain level. Prior to transmission, an MS monitors the received pilot signal power levels from nearby BSs, and chooses its home BS according to the maximum received pilot signal power. It is assumed that MSs, BSs, and MSCs are properly designed such that, while tracking the signal from the home BS, an MS searches for all the possible pilots and maintains a list of all pilots whose signal power levels are above a prescribed threshold. This list is transmitted to the MSC periodically through the home BS. The MSC uses the information to make a decision on when handoff should start and to estimate the mobility information. In this paper, the mobility information is defined to be the probabilities that an MS will be active in other cells at future moments. When a call request arrives, the MSC uses the mobility information of all the MSs in the cell and in the neighboring cells, together with their traffic characteristics, to estimate whether there are sufficient resources available to accommodate the new call without degrading QoS of the calls already in service.

Fig. 1 shows a uniform grid of hexagonal cells, where the MS under consideration is located at point M . For simplicity of presentation, we will focus on the mobility information and effective bandwidths of the MS related to its home BS (denoted as BS 0) and to its six first-tier neighboring BSs (denoted as BS 1, BS 2, ..., BS 6). Let $d_{i,t}$, $i = 0, 1, \dots, 6$, denote the distance between the MS and BS i at time t . It is assumed that, with a properly designed transceiver, the channel disturbance is mainly due to shadowing and path loss. The local mean of the pilot signal power from BS i received at the MS can be expressed as [16]

$$p_{i,t} = \frac{P_i}{d_{i,t}^\alpha} = D_i^{-\alpha} r_i^{-\alpha} v_i \quad (1)$$

where α is a constant proportional to the transmitted signal power, r is the path loss exponent, D_0 is the close-in reference distance which is determined from measurements close to the transmitter, and $\eta(t)$ in dB at any t is a Gaussian random variable (with zero mean and standard deviation σ_s) characterizing the shadowing phenomenon. For $l \neq k$, $\eta_l(t)$ and $\eta_k(t)$ are independent random processes. If the transmit power levels of all the pilot signals are the same, then $\eta_l(t) = \eta_k(t)$ for $l, k = 0, 1, \dots, 6$. $v_l(t)$ represents background noise power and multiple access interference (MAI) from the information-bearing signals in the forward link to all the MSs. When there are a large number of users in the system, the MAI can be modeled approximately by a Gaussian random process.

Similarly, in the reverse link, the propagation loss $\eta_l(t)$ from the MS to BS l is proportional to the product of the r th power of distance and a log-normal component characterizing the shadowing phenomenon, given by

$$\eta_l(t) = \frac{1}{4} d_l^r \eta_l(t) + 10 \log_{10} \eta_l(t), \quad (2)$$

where $\eta_l(t)$ in dB at any t is a Gaussian random variable with zero mean and standard deviation σ_s . For the MS at point M in Fig. 1, suppose at time t , the received power of the signal from this MS at its home base station BS 0 is $P_{r,0}(t)$, then the received power of the signal from this MS at the neighboring BSs can be expressed as

$$P_{r,l}(t) = \frac{1}{4} P_{r,0}(t) \frac{d_l^r}{d_0^r} 10^{\frac{1}{4} (\eta_l(t) - \eta_0(t))} 10^{\frac{1}{4} (\eta_l(t) - \eta_0(t))}, \quad l = 1, 2, \dots, 6; \quad (3)$$

In the wideband CDMA cellular system, soft handoff is adopted since it can extend CDMA cell coverage and increase reverse link capacity [17], [18]. Soft handoff happens when an MS moves into the overlapping cell coverage area of two or more BSs. The pilot channel bit energy to noise-plus-interference density ratio $\gamma_{E_b} = I_0 \gamma_{E_b}$ is used as the handoff measurement quantity. For simplicity, it is assumed that, in soft handoff, an MS is connected to two nearest BSs with strongest pilot signals, while it is power controlled by the BS that requires it to transmit at the smaller power. Consider that an MS moves into the soft handoff region from cell l to cell k . If cell k does not have enough resources to accept the handoff call when the MS moves out from the overlapping region, the call has to be dropped to guarantee the QoS of the existing calls in cell k . It should be mentioned that, during the soft handoff, the signal transmitted by the MS is received at both the BSs. With selection diversity at the receiving end, the required transmitted power of the MS (and, hence, the system resource) is reduced as compared with that in the hard handoff situation.

2.1 Traffic Model

The initial position of each MS is assumed to be uniformly distributed within the cell. We consider the case that all MSs in their home cell are perfectly power controlled. Hence, the received bit energy to noise-plus-interference ratios at the home BS from all the connections of the same class traffic are the same. The input traffic generated by the MSs is categorized as voice, video, and data traffic. Each traffic type has its own traffic characteristics and QoS requirements.

Each voice traffic flow is modeled by a two-state Markov process (i.e., an ON-OFF source), with a probability of

being in the ON state. The probability α is also known as voice activity factor. In the ON state, a voice connection has the constant transmission rate R_s kbps. The new voice call arrival process is Poisson with average arrival rate λ_s and exponential call duration with mean value μ_s^{-1} . The required bit energy to noise-plus-interference density ratio is $\gamma_{E_b} = I_0 \gamma_{E_b}$.

Each video traffic flow, also a real-time service, is modeled by N_v ON-OFF minisources [19]. At the call level, video calls follow the same model as that of the voice calls, with parameters α_v , λ_v , and $\gamma_{E_b} = I_0 \gamma_{E_b}$, respectively.

The data traffic has a minimum required transmission rate R_d . The data calls arrive according to a Poisson model with parameters λ_d , each having an exponential file size with mean value μ_d^{-1} . The required bit energy to noise-plus-interference density ratio for data traffic is $\gamma_{E_b} = I_0 \gamma_{E_b}$.

Each of the voice, video, and data services can further be divided into a number of traffic classes, depending on the traffic parameters and QoS requirements.

3 INTRACELL AND INTERCELL EFFECTIVE BANDWIDTH

We first consider a single-cell system with homogeneous traffic. Let N denote the number of admitted MSs of the same class traffic and W denote the total system frequency bandwidth in Hz for the reverse link. The required value of the received bit energy to noise-plus-interference density ratio at the BS is denoted by $\gamma_{E_b} = I_0 \gamma_{E_b}$. The transmission rate of user i at time t is a random variable R_i , $i = 1, 2, \dots, N$. The received signal power to noise-plus-interference density ratio (SNIDR) of the user i signal, γ_i , is then

$$\gamma_i = R_i \gamma_{E_b} = I_0 \gamma_{E_b}, \quad (4)$$

which is a random variable with mean γ and variance σ^2 .

The number of calls that can be admitted to the system (i.e., the upper bound of the admission region), N should be limited so that the required $\gamma_{E_b} = I_0 \gamma_{E_b}$ can be guaranteed for each and every admitted call. The N value should be chosen such that the following relation [3]

$$\frac{P_i}{\sum_{j=1}^N P_j} \leq W, \quad i=1, 2, \dots, N; \quad (5)$$

holds at any t for all $i = 1, 2, \dots, N$, where P_i denotes the received power level from user i . By summing both sides of (5) over all the N calls, we have

$$\sum_{i=1}^N \frac{P_i}{\sum_{j=1}^N P_j} \leq W; \quad (6)$$

Let α denote the QoS requirement of outage probability which is the probability that the required $\gamma_{E_b} = I_0 \gamma_{E_b}$ cannot be achieved. The admission region (6) can be specified by

$$\frac{P_i}{\sum_{j=1}^N P_j} \leq W, \quad i=1, 2, \dots, N; \quad (7)$$

As γ_i are independent and have identically distributed random variables with finite mean and variance, $\sum_{i=1}^N \gamma_i$ can be approximated by a Gaussian random variable for a large N , based on the central limit theorem. Then, (7) becomes

$$P(X > W) = \frac{1}{N} \int_0^W f(x) dx; \quad (8)$$

where X is a zero-mean unit variance (standard) Gaussian random variable. Inequality (8) is satisfied if and only if $W \leq \frac{1}{N} \int_0^W f(x) dx$, where $f(x)$ is defined by

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}; \quad (9)$$

Furthermore, the admission region can be determined by the set of points satisfying the inequality

$$B \leq W; \quad (10)$$

The parameter B is referred to as intracell effective bandwidth of each call, which can be calculated by [3]

$$B = \frac{1}{W} \int_0^W f(x) dx; \quad (11)$$

where $W = \frac{1}{N} \int_0^W f(x) dx$. The effective bandwidth depends on the transmission rate characteristics, the QoS requirements, and the statistical multiplexing with other calls at the BS.

Next, we consider a multicell system with heterogeneous traffic flows. Let K denote the number of cells, J the number of traffic classes, and N_{kj} the number of class j connections in cell k , with $k = 1, 2, \dots, K$ and $j = 1, 2, \dots, J$. The SNIDR value of connection i of class j in cell k can be expressed in terms of its (random) bit rate R_{kji} and the required bit energy to noise-plus-interference density ratio $E_b = I_0 / \sigma^2$, given by

$$\begin{aligned} R_{kji} &\leq R_{kji} E_b = I_0; \\ k &= 1, 2, \dots, K; \\ j &= 1, 2, \dots, J; \\ i &= 1, 2, \dots, N_{kj}; \end{aligned} \quad (12)$$

The admission region of cell k , denoted by the set $f(N_{k1}, N_{k2}, \dots, N_{kJ})$ for the J classes of calls, is determined by [3]

$$P \left(\sum_{k=1}^K \sum_{j=1}^J \sum_{i=1}^{N_{kj}} X_{kji}^l > W \right) \leq \alpha; \quad l = 1, 2, \dots, K; \quad (13)$$

where X_{kji} are independent random variables with distributions indexed by j , and X_{kji}^l models the interference seen at BS l receiver caused by connection i of class j in cell k when the home BS receives a unit power from the MS. Note most of the X_{kji}^l values are zero if we consider interference from the MSs only in the neighboring six cells. By applying the Gaussian approximation procedure to each of the K constraints in (13), the admission region of cell k can be obtained in the form

$$\sum_{k=1}^K \sum_{j=1}^J B_{kj}^l N_{kj} \leq W; \quad (14)$$

where B_{kj}^l is the effective bandwidth at cell l of a class j connection in cell k . The resources by a class j call in its home cell (cell k) is represented by the intracell effective bandwidth B_{kj}^k and in neighboring cell $l \neq k$ is represented by the intercell effective bandwidth B_{kj}^l . If we consider the intercell interference from an MS only in its

nearest six neighboring cells, then the intercell effective bandwidth is zero beyond the six first-tier neighboring cells. For notation simplicity, in the following, we use B_0 to denote the intracell effective bandwidth and B_l to denote the intercell effective bandwidth of the target MS seen in neighboring cell l ($l = 1, 2, \dots, 6$).

In the single-cell environment with homogeneous traffic, the effective bandwidth of a connection can be obtained easily since there is no interference from other cells. In the multicell system with heterogeneous traffic, the interference received at the BS from an MS in another cell, corresponding to the X_{kji}^l term in (13), is determined by the location of the MS and the propagation parameters, which makes the calculation of the intercell effective bandwidth quite complex. Assumptions made to simplify calculation can result in inaccuracy. An efficient and simple way to calculate the intercell effective bandwidth is needed to cope with the calculation complexity. Here, we propose using a fuzzy effective bandwidth estimator, as discussed in the next section.

4 DESIGN OF THE FUZZY CAC SCHEME

The structure of the proposed fuzzy call admission controller is shown in Fig. 2. The controller consists of four subsystems:

1. The fuzzy effective bandwidth estimator estimates the intercell effective bandwidth of a call according to its intracell effective bandwidth, which is determined by its traffic characteristics, and the received pilot signal power levels measured at the MS.
2. The fuzzy mobility information estimator estimates the MS mobility information (i.e., the probabilities that the MS will be active in the six neighboring cells at future moments) according to the received pilot signal power levels measured at the MS. The mobility information is used to determine the amount of bandwidth to be reserved in each of the neighboring cells for handoff calls.
3. The network resource estimator estimates the available resource that the system can supply according to the measured $E_b = I_0 / \sigma^2$ value of a traffic class and bandwidth reservation information.
4. The fuzzy call admission processor makes the decision on whether to accept or reject the call request according to the MS effective bandwidth, mobility information, and resource availability in the system.

4.1 Fuzzy Effective Bandwidth Estimator

In general, the larger the power received at a BS from an MS in another cell, the larger the intercell effective bandwidth used by the MS, and vice versa. When the intracell effective bandwidth of an MS is determined according to its traffic characteristics and system parameters, the relationship between the inter and intracell effective bandwidths can be mapped to the relationship between the power levels received, respectively, at the BSs in the neighboring cells and the home cell. In addition, the pilot signal power received by the MS in the forward link is a good indication of the mean power received at the corresponding BS in the reverse link; the received pilot signal power levels at the MS can then be used to reflect the relationship between inter and intracell effective bandwidths for the MS. In the

Fig. 4. Functional block diagram of the fuzzy mobility information estimator.

fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy If-Then rules in the fuzzy rule base into a mapping from the fuzzy sets of the pilot signal powers to the fuzzy sets of the effective bandwidths.

Given Fact : P_0 is PF_0 and P_1 is PF_1 and ... and P_6 is PF_6

Consequence : B_1 is BF_1 and ... and B_6 is BF_6

where PF_0 , PF_1 , and BF_1 ($l = 1; 2; \dots; 6$) are linguistic terms for P_0 , P_1 , and B_1 , respectively. The fuzzy rule base can be generated from training data. The data can be collected from a real system or generated by computer simulation, based on the traffic characteristics, propagation model, QoS parameters, and cell structure. Given a set of desired input-output data pairs, a set of fuzzy If-Then rules can be generated. In addition, a degree which reflects the expert belief of the importance of a rule can be assigned to each rule.

The defuzzifier performs a mapping from the fuzzy sets to a crisp vector (with numerical values). Among the commonly used defuzzification strategies, the center average defuzzification method yields a superior result [20] and is, therefore, used in all the defuzzifications in the fuzzy inference system shown in Fig. 2. The estimation at the defuzzifier output is given by

$$B_l = \frac{\sum_{m=1}^M P_m C_m P_0 P_1 B_l^m}{\sum_{m=1}^M C_m P_0 P_1} \quad (15)$$

where B_l is the numerical value of the estimated effective bandwidth, B_l^m is the center value of the output region of rule m , and C_m is the normalized degree of rule m .

4.2 Fuzzy Mobility Information Estimator and Bandwidth Reservation

User mobility information can be used to assist user mobility management, to manage network resources, and to analyze handoff algorithms in wireless networks. Different from the previous research efforts on mobility information, which focused on statistics such as mobility model [21], user location tracking and trajectory prediction [22], channel holding time [23], cell boundary crossing rate [24], mean handover rate [25], and cell residence time [26], we are interested in the probabilities that an MS will be active in a neighboring cell at future moments [27]. The mobility information with reasonable accuracy facilitates statistical multiplexing and plays an important role in efficient resource management of the wireless cellular system [28]. In general, if an MS is closer to a BS, then the propagation path attenuation from the BS to the MS is smaller, and vice versa. Hence, if the BS transmits a pilot signal with constant power, then the received power of the

pilot signal at the MS carries the information of the distance between the MS and the BS. Since the probability that the MS will be active in a particular cell at a future moment is a function of the current distance between the MS and the nearby BS, the probability can be estimated based on the real-time measurement of the received pilot signal power at the MS from the BS. Furthermore, the probability depends on the movement pattern of MS (such as movement trajectory). Although the movement patterns of MSs are random in nature, the movement of an individual MS follows a relatively smooth trajectory most of the time. That is, the location of an MS at a future moment depends on its locations at the current moment and previous moments. As a result, it is possible to predict the mobility information based on the current and previous measurement data. As discussed preceding, due to the random phenomenon of shadowing and inaccurate measurements caused by MAI, it is very difficult to accurately describe the relationship between the strength of the received pilot signal and the mobility information, e.g., by a mathematical expression. To overcome the difficulty, an adaptive fuzzy inference prediction system consisting of a fuzzy inference system and a recursive least square (RLS) predictor is employed to estimate and predict the MS mobility information.

Fig. 4 shows the functional block diagram of the fuzzy mobility information estimator. It consists of two subsystems: a fuzzy inference system which is similar to the fuzzy effective bandwidth estimator, and an RLS predictor. The fuzzy inference system takes the measurements of the received pilot signal power levels at the MS (P_0 , and P_1 , $l = 1; 2; \dots; 6$) as the input, and estimates the probability that the MS will be active in cell l at time t_n , $p_{l,n}$ ($l = 0; 1; 2; \dots; 6$), based on the measured pilot signal strengths at time t_n . Before measurements at t_{n-1} are available, the RLS predictor predicts the probability that the MS will be active in cell l at time t_{n-1} for $l = 1; 2; \dots$, based on the estimates from the fuzzy inference system up to time t_n . In Fig. 4, $p_n = [p_{0,n}; p_{1,n}; \dots; p_{6,n}]$ and $p_{n-1} = [p_{0,n-1}; p_{1,n-1}; \dots; p_{6,n-1}]$. A detailed discussion of the fuzzy inference prediction system can be found in [27].

With the mobility information, if an MS has a maximum probability, p_{\max} , to handoff to a neighboring cell and if this probability is larger than a threshold $p_{\max,t}$, then a proper amount of resources should be reserved for the MS at the most likely future home BS. The amount of the reserved resources for the MS is $p_{\max} B_{0,j}^0 - B_{0,j}^l$. The total amount of reserved resources at each BS is subject to a minimum value $B_{r,\min}$ and a maximum value $B_{r,\max}$.

4.3 Network Resource Estimator

In the network resource estimator, a fuzzy residual bandwidth estimator is explored to estimate the residual bandwidth (denoted by B_s) of each cell according to the $E_b = I_0$ measurement of one specific traffic class in the cell.

Each BS collects the $E_b = I_0$ measurement of this traffic class periodically, which is denoted by $\mu_{E_b=I_0}$. There exists a residual bandwidth if $\mu_{E_b=I_0} > \mu_{E_b=I_0}$ and the residual bandwidth increases with the value of $\mu_{E_b=I_0}$. The relationship between the $E_b = I_0$ measurements and the residual bandwidth of the BS can be mapped to the fuzzy inference rules in the fuzzy residual bandwidth estimator with carefully defined membership functions of $\mu_{E_b=I_0}$ and B_s .

With the information of

1. the residual bandwidths at the BSs,
2. the intra and intercell effective bandwidths of the new call, and
3. the reserved bandwidths for the existing calls at nonhome BSs, the available bandwidths that the home BS, and its neighboring BSs are able to supply to the new call can be obtained.

Let $B_{a,l}$ denote the available bandwidth in cell l , $B_{s,l}$ the residual bandwidth of cell l , and $B_{r,l}$ the summation of the reserved bandwidths in cell l for all the on-going calls in the system. The available bandwidth at cell l is given by

$$B_{a,l} = B_{s,l} - B_{r,l}; \quad l = 0; 1; \dots; 6; \quad (16)$$

4.4 Fuzzy Call Admission Processor

As shown in Fig. 1, when a new class j call requests for a connection in cell 0, the MSC first calculates its intracell bandwidth B_0 , intercell bandwidth B_l , and residual bandwidth of the home cell and each neighboring cell $B_{s,l}$, and then checks the available bandwidth in both its home cell and neighboring cells, $B_{a,l}$, $l = 0; 1; \dots; 6$. If $B_{a,0} \geq B_0$ and $B_{a,l} \geq B_l$ for all $l = 1; 2; \dots; 6$, the new call will be accepted; otherwise, it will be rejected. If the request comes from an MS in service in a neighboring cell, the handoff call will be admitted as long as $B_{s,0} \geq B_0$ and $B_{s,l} \geq B_l$ for all $l = 1; 2; \dots; 6$.

Due to the random nature of user movement and transmission rate of a multimedia traffic flow, reserving resources in the neighboring cells to keep a low handoff call dropping probability results in the waste of the reserved resources from time to time. This issue cannot be solved by the above fixed rule CAC scheme since it does not adapt to the traffic load dynamics. To better make use of the system resources, a fuzzy CAC processor (FCACP) can be employed to process the new call requests, instead of using the fixed rule control. The FCACP takes the effective bandwidths of a new call, the available bandwidth information that its home cell and its neighboring cells can supply, and the outage probability requirements as the input linguistic variables, and uses a fuzzy inference system to determine whether or not to accept the new call. The structure of the FCACP is similar to the fuzzy effective bandwidth estimator. The term sets for effective bandwidth B_l , available bandwidth information in its home cell $B_{a,0}$, available bandwidth information in its neighboring cells $B_{a,l}$ ($l = 1; 2; \dots; 6$), and QoS indicator Q are defined as $U \mu_{B_l} \approx 1/4$ fS (small), SM (small to medium), M (medium), ML (medium to large), L (large), $U \mu_{B_{a,0}} \approx 1/4$ fNE (not enough), E (enough), ME (more than enough), $U \mu_{B_{a,l}} \approx 1/4$ fNE; E; MEg, and $U \mu_Q \approx 1/4$ fS (satisfied), NS (not satisfied). The term set for output linguistic variables D of the FCACP is $U \mu_D \approx 1/4$ fA (accept), WA (weakly accept), WR (weakly reject), R (Reject). The output of the FCACP is a crisp value $D \in [0; 1]$. A call request

will be accepted when the value of D is larger than a preset threshold value D_0 .

4.5 Discussion

The complexity of the proposed fuzzy call admission controller may be a concern, especially when the size of the system is large in terms of the cell number, the traffic class number, and the admission region size. It is possible that the calculation is more time-consuming than other call admission control schemes, due to the number of input linguistic variables and their membership functions. One practical way to overcome the calculation load is to establish a table of fuzzy-controller results offline, and using table look-up approach to make the CAC decision on-line. Taking into account that MSCs usually have very powerful calculation/processing capability, it is expected that the table look-up approach should not pose an implementation problem.

Even though the fuzzy CAC scheme is proposed for wideband CDMA communications, the principles of the fuzzy CAC can be applied to cellular communication systems in general, including time-division multiple access (TDMA) and frequency-division multiple access (FDMA) systems. In TDMA and FDMA systems, we do not need to consider the intercell effective bandwidth due to the orthogonality among the transmission channels, which simplifies the CAC process.

The proposed fuzzy call admission controller consists of four fuzzy inference subsystems. The stability and robustness of the proposed controller should be addressed. Robustness of fuzzy inference systems and approaches to designing stable fuzzy control systems (in the sense of exponential stability and input-output stability) have been discussed in [15]. Stability of closed-loop systems with fuzzy logic controllers has been investigated (e.g., in [29]). In general, robust fuzzy control is an open field and much work remains to be done. The fuzzy call admission controller shown in Fig. 2 has three features related to the stability and robustness:

1. it is an open loop system in terms of the CAC process for each call;
2. the output of the mobility information estimator is bounded (by the definition of probability); and
3. the amount of resources reserved for handoff calls is also bounded by design parameters $B_{r,min}$ and $B_{r,max}$.

The potential performance oscillations can be reduced (or eliminated) if the mobility information and the amount of resource reservation are updated relatively fast when compared with the system dynamics (such as MS moving speeds). However, further investigation is necessary.

5 NUMERICAL RESULTS

The performance of the proposed fuzzy call admission controller is evaluated via computer simulation and is compared with the CAC schemes previously proposed in [30], [31].

The CDMA system having reverse link bandwidth $W = 3.75$ MHz and $K = 25$ cells, as shown in Fig. 5, is simulated. Each cell has a radius of 1,500 meters. There are $J = 3$ traffic classes, each call having a probability of 0.5, 0.1, and 0.4 to be voice, video, and data call, respectively. The movement pattern of an MS is modeled as follows:

Fig. 5. The cellular layout of the simulation system.

1. The initial location of each new call is uniformly distributed in the 25 cells.
2. The velocity of each MS is uniformly distributed between 5m (meter)/s (second) and 20m/s, and does not change with time.
3. The MS moves to any of its adjacent cells with equal probability, and its moving direction remains the same during the whole connection.
4. Only the MSs in these 25 cells are under consideration.

Each voice call has a voice activity factor $\alpha \approx 0.4$ and the transmission rate $R_s \approx 9.6$ kbps. Each video connection is modeled as the superposition of $N_v \approx 19$ independent mini ON-OFF sources. Each minisource generates information at rate of 9.6 kbps during an ON period. The average length is 0.2 s for each ON period and 0.8 s for each OFF period. Each data connection requires a minimum transmission rate of $R_d \approx 19.2$ kbps. The required E_b/I_0 value is 7dB for voice and video connections, and 9dB for data connections. The QoS requirement of outage probability is ≈ 0.01 for all voice, video, and data calls. The parameters in (1) and (3) are: $\alpha \approx 1$, $D_0 \approx 100$ m, $r \approx 4$, and $s \approx 2$ dB. The parameters for resource reservation are $P_{\max,t} \approx 0.3$, $B_{r,\max} \approx 375$ kHz, and $B_{r,\min} \approx 50$ kHz. The mobility information is updated every 0.1s and is predicted for $L \approx 1, 2$, and 3. The effective bandwidth of each call in the single-cell homogeneous traffic situation can be calculated to be 22kHz for voice, 212kHz for video, and 152.5kHz for data, respectively.

In order to generate fuzzy inference rules for estimating the intercell effective bandwidth of an MS, membership functions for each fuzzy variable should be determined, and training data are needed. To choose the type and number of membership functions, it is necessary to take into account both computational efficiency and adaption complexity of the fuzzy inference system. Gaussian, triangle, and trapezoid functions are the most commonly used membership functions. The Gaussian function is chosen here as the format of membership functions because it is a better reflection of the propagation model where the effect of shadowing (in dB) is a normal random variable. To obtain the parameters of the membership functions, the distance between an MS and a BS in one of its neighboring cells is divided into nine equal segments, and 10,000 MSs are simulated in each segment and the values of mean and variance of pilot signal strength are obtained as the parameters of membership functions of the pilot signal strength. The membership function parameters of intercell effective bandwidth are determined by simulating MSs in

Fig. 6. Membership functions of the received pilot signal strength at the MS.

the center of each distance range and applying inequality (13). Fig. 6 shows the membership functions of variables P_0 and P_1 . Fig. 7 shows the membership functions of the intercell effective bandwidth B_1 of a voice call. The training data are generated through computer simulation to obtain the fuzzy inference rules. Table 1 shows some rules of estimating intercell effective bandwidth for a voice call. The fuzzy residual bandwidth estimator is used to estimate the residual effective bandwidth of the system according to the E_b/I_0 measurements. The term sets for E_b/I_0 and B_s used are in the form of $U(E_b/I_0) \approx \frac{1}{4} f S_1; S_2; \dots; S_{35} g$ and $U(B_s) \approx \frac{1}{4} f B_1; B_2; \dots; B_{35} g$, respectively. Table 2 shows some fuzzy inference rules of the fuzzy residual bandwidth estimator. Table 3 shows some rules of the FCACP.

To evaluate the effectiveness of the proposed FCAC scheme, two other CAC schemes, received power-based call admission control (RPCAC) [30] and nonpredictive call admission control (NPCAC) [31], are also examined. For NPCAC, a connection request is approved if the following conditions are satisfied:

Fig. 7. Membership functions of the effective intercell bandwidth of a voice call.

TABLE 1
Fuzzy Inference Rules of the Intercell Effective Bandwidth Estimator for a Voice Call

TABLE 2
Fuzzy Inference Rules for Residual Bandwidth Estimator

TABLE 3
Fuzzy Inference Rules for the CAC Decision, where $l = 1; 2; \dots; 6$

$$\frac{W_d}{W_T} \leq \frac{W_a}{REB_l} \quad \text{for neighboring cell } l$$

where W_d is the equivalent bandwidth of the connection, which is the product of the required equivalent signal to noise-plus-interference ratio, γ_d , and bit rate R_d , i.e., $W_d = \gamma_d R_d$; W_T is the system bandwidth, W_a is the total equivalent bandwidth occupied by all active users in that cell; and REB_l is the cell's remaining equivalent bandwidth.

In the simulation, the values of γ_d and γ_a are 0.70 and 0.08, respectively. For RPCAC, a connection request is accepted at BS 0 as long as the total received power Z_0 at the BS is less than a predefined threshold value Z_0 . Z_0 is equal to $0.9Z_{\max}$ in the simulation, where Z_{\max} is the maximum power level received at the BS to satisfy the carrier-to-interference ratio requirement.

Fig. 8 shows the outage probability of the system with respect to different call arrival rates for FCAC, RPCAC, and NPCAC, respectively. It can be seen that the FCAC and the NPCAC can always satisfy the outage probability requirement even under the heavy traffic load conditions, while the RPCAC cannot meet the requirement during heavy traffic load periods. Figs. 9, 10, and 11 show the new call blocking probability (NCBP) and handoff call dropping probability (HCDP) for voice, video, and data calls, versus the corresponding call arrival rate, respectively. It can be seen that the NPCAC has the highest NCBP and lowest HCDP, while RPCAC has the lowest NCBP and highest HCDP. The FCAC has both lower NCBP and HCDP, which is desirable. Figs. 12, 13, and 14 show the mean admitted number of voice, video, and data calls in the system as a function of the corresponding call arrival rate, respectively. The system resource utilization efficiency increases with the average number of active users. It can be seen that, while the mean number of active users for FCAC and RPCAC are similar, the mean number of active users for NPCAC is lower than those of the FCAC and RPCAC.

For RPCAC, the call admission decision for one particular cell is made based on the total received power at that cell, without considering the power level in any other cell. When a call is accepted into a cell, it will not only increase the received power level in the cell, but also increase the received interference levels in the neighboring cells. If the traffic load in the neighboring cells is not taken into account, the QoS requirements of the MSs in the target cell and its neighboring cells may not be satisfied. Even though the RPCAC can achieve a lower new call blocking

Fig. 8. Outage probability of voice calls versus the voice call arrival rate.

Fig. 9. New call blocking probability and handoff call dropping probability for voice calls.

Fig. 10. New call blocking probability and handoff call dropping probability for video calls.

probability and higher system resource utilization, the outage probability of the whole system is not satisfied during heavy traffic load periods. In addition, the RPCAC does not differentiate new calls and handoff calls, resulting in the similar new call blocking and handoff call dropping probabilities. For the NPCAC, the MS's intercell effective bandwidth is taken into account in the call admission decision procedure, but the intercell effective bandwidth is represented by the product of a constant and its equivalent bandwidth. This is not true in a CDMA cellular system since the intercell effective bandwidth of an MS is

dependent on the MS location and other factors such as wireless channel conditions. It is not easy to choose a suitable value for the constant: If a large value is chosen, the resources in other cells may be wasted. If a small value is chosen, the resources in other cells may not be enough if the call is accepted in its home cell. The advantage of the NPCAC is that the QoS requirement of outage probability is satisfied with properly chosen parameters. The disadvantage is that it achieves a high new call blocking probability and low system resource utilization. For the FCAC, the intercell effective bandwidth of an MS is calculated

Fig. 11. New call blocking probability and handoff call dropping probability for data calls.

Fig. 12. The average number of active voice calls in the system.

according to the real-time signal strength measurements, the handoff calls are given higher priority by adaptively reserving a proper amount of resources according to the mobility information, and the new call admission decision is made by taking into account the new call characteristics, system resource availability situation, and QoS provisioning of the system, which dynamically adapts to the current system status. As a result, the FCAC can achieve efficient resource utilization and, at the same time, meet the QoS requirement of outage probability.

6 CONCLUSION

A fuzzy CAC scheme for wideband CDMA cellular communications has been proposed to meet the challenges in CAC due to user mobility, limited radio spectrum, heterogeneous and dynamic nature of multimedia traffic, and QoS constraints. The fuzzy approach can overcome measurement errors, mobility and traffic model uncertainty, and avoid the requirements of complex mathematical relations among various design parameters. The resource requirement of each call is presented in terms of intracell

Fig. 13. The average number of active video calls in the system.

Fig. 14. The average number of active data calls in the system.

and intercell effective bandwidths. The user mobility information is estimated and predicted based on the measurements of the pilot signal power levels received at the MS. The CAC decision is based on the resource availability where handoff calls are given with high priority in comparison with new calls via resource reservation. Simulation results show that the fuzzy CAC scheme can achieve QoS satisfaction in terms of the outage probability, and achieve lower new call blocking probability, lower handoff call dropping probability, and higher resource

utilization efficiency, when compared to the previously proposed RPCAC and NPCAC schemes.

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