PAPER

Forward Link Performance of Combined Soft and Hard Handoff in Multimedia CDMA Systems

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SUMMARY The soft handoff is widely adopted in code division multiple access (CDMA) systems for its many advantages mainly resulting from site diversity. However, in the forward link, other cell interference can be increased by soft handoff, decreasing system capacity. In future mobile systems, provision for the sufficient forward link capacity is very important since the forward link load is much higher than the reverse link load in mobile multimedia services such as Internet access. In this paper, we consider a combined handoff strategy in which voice services are provided with soft handoff whereas data services are supported with hard handoff. We analyze the effect of handoff method on the forward link performance. The performance measures we use are the outage probability of the bit energy to noise density ratio and the capacity based on the outage probability. As a result, we show that the combined handoff is very useful in CDMA cellular networks supporting both voice and data services simultaneously.

key words: *CDMA, forward link capacity, combined soft and hard handoff, multimedia service*

1. Introduction

Code division multiple access (CDMA) has become the most promising multiple access technology for third-generation cellular systems supporting multimedia services. CDMA systems, including wideband CDMA (WCDMA) systems for International Mobile Telecommunications-2000 (IMT-2000), employ the *soft handoff* method. With the soft handoff, a mobile can be connected simultaneously to several bases. That is, a mobile in soft handoff procedure transmits signal to and receives signal from more than one base. We refer to the serving bases in the handoff procedure as "active bases" and to the set of active bases as "active set." The case in which only a single base is in the active set during the handoff procedure corresponds to the *hard handoff*.

In general, soft handoff attains site diversity gain. The site diversity lowers the call dropping rate during handoff and can enhance the reverse link (from mobile to base) capacity [1]. However, the latter is not the case in the forward link (from base to mobile) [2], [3]. Note that no extra channel (actually, power) is required to accomplish soft handoff in the reverse link. Instead, in the forward link, multiple bases assign resources to the same mobile. For the overall system, the increase in other cell interference to mobiles can outweigh the site diversity gain from soft handoff.

From the service point of view, the gain and loss of soft handoff in the forward link vary with traffic (service) classes. For voice services, the advantages of soft handoff, e.g., reduced call drop rate, can compensate for the capacity loss.

However, for data services, e.g., Internet access, soft handoff may not be profitable since the characteristics of data session are the long duration of a session, the burst nature of data transmission, the retransmission mechanism, and the loose delay constraint. Therefore, the dropping probability of a data session using hard handoff may be usually lower than that of a voice call. On the other hand, improving the forward link capacity is more essential in data services, because of traffic asymmetry between forward and reverse links [4]–[6]. As a result, some recent proposals for forward link data services consider only hard handoff (e.g., [7]).

The forward link capacity without soft handoff has been analyzed in [8], [9]. Recently, [10] and [11] have investigated the forward link capacity with soft handoff. In these studies, however, the mixture of several classes of traffic has not been considered. In [12], forward link capacity with several classes of traffic and soft handoff has been analyzed. In [13], we have considered and analyzed a combined handoff supporting multiple traffic classes. With the combined handoff, voice services are provided with soft handoff whereas data services are supported with hard handoff. It was shown in [13] that combined handoff outperforms soft handoff in forward link capacity.

In [13], we have used the definition of capacity based on "average value" of bit energy to noise density ratio (E_b/N_0). Moreover, we have assumed a very simple power allocation method for the sake of convenience. Although the results are sufficient to investigate the trend in pros and cons of soft and hard handoff methods, it may not reflect the practical power-controlled forward link.

In this paper, we analyze the effect of handoff

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method on the forward link performance more carefully. The performance measures we use are based on E_b/N_0. A forward link power allocation method assigns transmission power according to the required values of E_b/N_0. The outage probability is defined as the probability that the power allocation method cannot find the solution to meet pre-defined required values of E_b/N_0 of all mobiles. Accordingly, we get realistic results that can be used in designing and operating CDMA cellular networks supporting both voice and data services.

The remainder of this paper is organized as follows. The next section describes the system model under consideration. Section 3 analyzes the forward link capacity. In Sect. 4, we investigate the effects of the parameter values on the capacity with some numerical results. Finally, the paper is concluded with Sect. 5.

2. System Model

We consider direct-sequence CDMA systems with bandwidth of B. A user's signal is spread over the entire bandwidth.

It is assumed that the service area consists of M identical hexagonal cells as exemplified in Fig. 1 (with $M = 19$). A base locates at the center of each cell. It is also assumed that all cells are statistically identical to each other from the viewpoint of cell loading. The mobiles are assumed to be uniformly distributed over the cell area.

Let $L_{i,m}$ and $d_{i,m}$ denote the link gain and distance from the mth base ($1 \leq m \leq M$) to the ith mobile, respectively. Hereafter, the subscript i in the notation denotes the ith mobile. We use a log-normal attenuation model to define shadowing or slow fading. Then, the link gain is given by

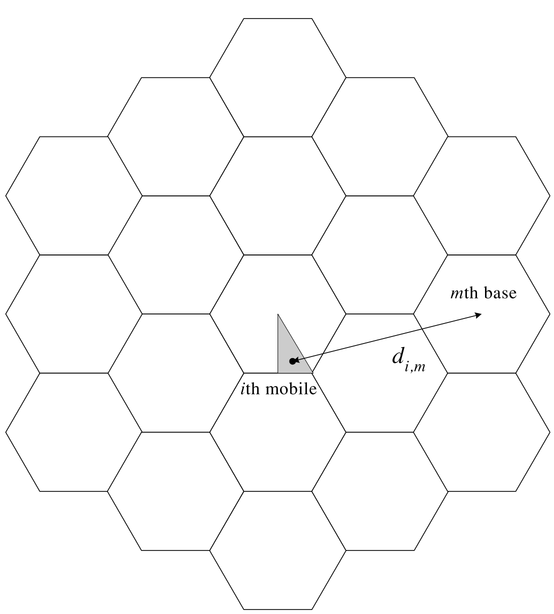

Fig. 1 Cellular structure under consideration.

$$L_{i,m} = d_{i,m}^{-\omega} 10^{\lambda_m/10}, \tag{1}$$

where ω is the path loss exponent, typically $3 \leq \omega \leq 5$, and $\lambda_1, \lambda_2, \cdots \lambda_M$ are independent and identical Gaussian random variables with zero mean and standard deviation of σ.

During soft handoff, the mobile is assumed to use the maximal ratio combiner to combine signals from active bases. The total transmission power for each base is assumed to be the same in order to consider the full traffic load in all cells.

For the forward link, power control at the base transmitter takes the form of power allocation according to the needs of individual mobiles. Let $J_{i,m}$ denote the total received power from the mth base to the ith mobile. Then, $J_{i,m}$ is the product of the total transmission power from the mth base and $L_{i,m}$. Let β denote the fraction of the total transmission power devoted to the traffic sources ($1-\beta$ is the fraction devoted to the control channel such as pilot). Then, $\beta J_{i,m}$ is the total received power devoted to traffic sources from the mth base to the ith mobile. Let $\phi_{i,m}$ denote the fraction of $\beta J_{i,m}$ devoted to the ith mobile. Then, $\phi_{i,m}\beta J_{i,m}$ is the desired received power from the mth base to the ith mobile. Note that the value of $\phi_{i,m}$ is zero for nonactive bases. Since we have assumed that all cells are statistically identical and the total transmission power for each base is the same, we may infer that $\phi_{i,m}$ becomes the same for active bases if the transmission power to the ith mobile from active bases are the same.

In practice, the transmission power to the ith mobile is controlled by feedback information from the ith mobile. Active bases that are connected with the ith mobile receive the same feedback information. Thus, under the assumptions that all active bases use the same initial transmission power and there is no error on feedback information, all active bases use the same transmission power for a mobile. In this case, all active bases have the same value for $\phi_{i,m}$. We assume in this paper that the value of $\phi_{i,m}$ is the same for active bases and simply denote it by ϕ_i.

There can be various classes of traffic in mobile multimedia systems. However, for the simplicity of discussion, we consider a system with only two classes, voice and data. A mobile is either voice or data one. An integrated services (multimedia) mobile is regarded as a combination of voice and data mobiles. Hereafter, the subscripts v and d in the notation denote voice and data traffic, respectively.

The traffic model under consideration is as follows. A mobile and its corresponding communication entity in the base are regarded as traffic sources. Sometimes, we also consider a call or a session between mobile and base as a traffic source. A traffic source alternates between active and inactive states. The class of a traffic source is characterized by its activity parameters and the transmission information rate. Source activity can be represented by an activity variable ψ that has Bernoulli distribution: ψ is equal to one with probability μ and to zero with probability $1-\mu$, where μ is defined as the activity factor. When the forward link source is in the active state, it transmits information with information rate of R (in bps). Therefore, the average information rate of a source is equal to μR.

The quality of service (QoS) for each class of traffic can be defined with various criteria. Among these, we herein consider the outage probability, denoted by P_{out}. Let γ denote the required E_b/N_0 for a class of traffic to guarantee the adequate QoS. We define P_{out} as the probability that the power allocation method cannot find the solution to meet γ, for all mobiles that communicate with a given base. Note that P_{out} is smaller than or equal to the probability that E_b/N_0 of a single arbitrary mobile is less than γ. The QoS requirement used in this paper is that P_{out} should be smaller than a predefined value, denoted by δ.

For a given number of data mobiles, denoted by H_d, the voice capacity C_v is defined as the possible maximum number of voice mobiles per base that satisfies the QoS requirements. The system with C_v voice mobiles and H_d data mobiles can satisfy the QoS requirements of both voice and data mobiles simultaneously. However, any increment of C_v or H_d results in failure to meet the QoS requirements. Similarly, for a given number of voice mobiles, denoted by H_v, we can define the data capacity C_d. Since the relationship between C_v and H_d is a duality of that between H_v and C_d, we only treat C_v herein. A more accurate definition of C_v will be given in the next section.

3. Forward Link Capacity

3.1 Capacity with Hard Handoff

We first consider capacity with hard handoff. With hard handoff, a mobile communicates with only one base at a time. From the viewpoint of the ith mobile, without loss of generality, bases can be respectively numbered from one to M according to the strength of received power as

$$J_{i,1} > J_{i,2} > J_{i,3} > \cdots > J_{i,M} > 0. \tag{2}$$

Then, the base with the highest received power is selected as the active base.

Since orthogonal channelizing codes are usually used in forward link, the factor denoted by φ is introduced to account for the interference reduction from the selected (first) base due to orthogonality [14]. If the tagged mobile (mobile i) is a voice one, the intracell interference is $\varphi(J_{i,1}-\beta\phi_{i,v}J_{i,1})$. Since $J_{i,1} \gg \beta\phi_{i,v}J_{i,1}$, the interference is approximately $\varphi J_{i,1}$. The intercell interference is $\sum_{m=2}^{M} J_{i,m}$. Thus, the E_b/N_0 of the ith voice mobile is given as

$$\left(\frac{E_b}{N_0}\right)_{i,v} = \frac{\beta\phi_{i,v}J_{i,1}/R_v}{(\varphi J_{i,1}+\sum_{m=2}^{M} J_{i,m})/B}. \tag{3}$$

Note in (3) that we ignored the thermal noise since it is negligible compared to the interference. $(E_b/N_0)_{i,v}$ should be equal to or greater than the required value γ_v. That is,

$$\left(\frac{E_b}{N_0}\right)_{i,v} \geq \gamma_v. \tag{4}$$

Let G_v be the processing gain of a voice traffic. That is, $G_v = B/R_v$. From (3) and (4), we get

$$\phi_{i,v} \geq \frac{\gamma_v(\varphi J_{i,1}+\sum_{m=2}^{M} J_{i,m})}{\beta G_v J_{i,1}} \stackrel{\text{def}}{=} \phi'_{i,v,h}, \tag{5}$$

where the subscript h in $\phi'_{i,v,h}$ means the "hard handoff."

According to a similar method and using a similar notation, the fraction of base power devoted to the ith data mobile is bounded as

$$\phi_{i,d} \geq \frac{\gamma_d(\varphi J_{i,1}+\sum_{m=2}^{M} J_{i,m})}{\beta G_d J_{i,1}} \stackrel{\text{def}}{=} \phi'_{i,d,h}. \tag{6}$$

We denote the number of voice and data mobiles that communicate with a given base as H_v and H_d, respectively. From the definition of ϕ'_i's, when the sum of all ϕ'_i of mobiles that are in active state is more than one, the power allocation method cannot find the solution of ϕ_i that meets the E_b/N_0 requirements of all mobiles.

Thus, the outage probability is given as

$$P_{\text{out}}(H_v,H_d) = \Pr\left(\sum_{i=1}^{H_v}\phi'_{i,v,h}\psi_{i,v} + \sum_{i=1}^{H_d}\phi'_{i,d,h}\psi_{i,d} > 1\right). \tag{7}$$

And the voice capacity with the given H_d is given as

$$C_v = \max[H_v : P_{\text{out}}(H_v,H_d) \leq \delta]. \tag{8}$$

3.2 Capacity with Soft Handoff

We assume two-way soft handoff in an unsectorized cell as follows. The mobiles in soft handoff state communicate with two bases. The other mobiles communicate with one base. The selection method of active bases is similar with that of hard handoff. The first base is always an active base. When the received power from the second base is more than the threshold level, denoted by ϵ, the second base also becomes an active base. In contrast, when the received power from the second base is less than ϵ, the second base disconnects the communication link with the mobile.

Let us define the soft handoff indication function of the ith voice mobile, denoted by $\zeta_{i,v}$, as

$$\zeta_{i,v} = \begin{cases} 1, & \text{if } J_{i,2} \geq \epsilon_v \\ 0, & \text{else.} \end{cases} \quad (9)$$

When $\zeta_{i,v}$ is zero, the first base transmits power for the ith voice mobile. When $\zeta_{i,v}$ is one, the first and the second bases transmit power for it.

The E_b/N_0 of the ith voice mobile at the output of the maximal ratio combiner is given as

$$\left(\frac{E_b}{N_0}\right)_{i,v} = \frac{\beta\phi_{i,v}J_{i,1}G_v}{\varphi J_{i,1} + \sum_{m=2}^{M} J_{i,m}} + \frac{\zeta_{i,v}\beta\phi_{i,v}J_{i,2}G_v}{\varphi J_{i,2} + \sum_{m=1,m\neq 2}^{M} J_{i,m}}. \quad (10)$$

Compared with (3), the second term of (10) is the gain factor in capacity, obtained from site diversity. The fraction of power devoted to the ith voice mobile is bounded as

$$\phi_{i,v} \geq \frac{\gamma_v}{\beta G_v}\left(\frac{J_{i,1}}{\varphi J_{i,1} + \sum_{m=2}^{M} J_{i,m}} + \frac{\zeta_{i,v}J_{i,2}}{\varphi J_{i,2} + \sum_{m=1,m\neq 2}^{M} J_{i,m}}\right)^{-1} \stackrel{\text{def}}{=} \phi'_{i,v,s}, \quad (11)$$

where the subscript s in $\phi'_{i,v,s}$ means the "soft handoff."

The fraction of power devoted to the ith data mobile is bounded as

$$\phi_{i,d} \geq \frac{\gamma_d}{\beta G_d}\left(\frac{J_{i,1}}{\varphi J_{i,1} + \sum_{m=2}^{M} J_{i,m}} + \frac{\zeta_{i,d}J_{i,2}}{\varphi J_{i,2} + \sum_{m=1,m\neq 2}^{M} J_{i,m}}\right)^{-1} \stackrel{\text{def}}{=} \phi'_{i,d,s}. \quad (12)$$

Let S_v and S_d denote the number of voice and data mobiles, respectively,that communicate with a given base. The outage probability is given as

$$P_{\text{out}}(S_v, S_d) = \Pr\left(\sum_{i=1}^{S_v}\phi'_{i,v,s}\psi_{i,v} + \sum_{i=1}^{S_d}\phi'_{i,d,s}\psi_{i,d} > 1\right). \quad (13)$$

Let P_{soft} be the probability that a mobile is in the soft handoff state. The value of P_{soft} depends on the value of ϵ in (9). For a given base, the number of voice (data) mobiles that are in soft handoff state is $S_vP_{\text{soft},v}$ ($S_dP_{\text{soft},d}$). Compared with hard handoff, $S_vP_{\text{soft},v}/2$ and $S_dP_{\text{soft},d}/2$ additional mobiles are included in the capacity of a base. The case where $P_{\text{soft}} = 0$ corresponds to the hard handoff.

In order to make the same traffic load as that for hard handoff, the given number of data mobiles S_d is set as

$$S_d = \frac{H_d}{1 - P_{\text{soft},d}/2}. \quad (14)$$

Similarly, the relation between H_v and S_v can be set as

$$H_v = S_v\left(1 - \frac{P_{\text{soft},v}}{2}\right). \quad (15)$$

In order to compare with hard handoff, the capacity is also normalized as

$$C_v = \left(1 - \frac{P_{\text{soft},v}}{2}\right)\max[S_v : P_{\text{out}}(S_v, S_d) \leq \delta]. \quad (16)$$

Compared with (8), $S_vP_{\text{soft}}/2$ and $S_dP_{\text{soft}}/2$ are the loss factors in capacity resulting from the increased number of mobiles in communication.

3.3 Capacity with Combined Handoff

We consider the combined handoff system that was proposed in [13] where soft handoff is applied to voice mobiles and hard handoff is applied to data mobiles.

With combined handoff, the ϕ of the ith voice mobile is given as (11), whereas that of the ith data mobile is given as (6). We denote the number of voice and data mobiles that communicate with a given base as S_v and H_d, respectively. The outage probability is given as

$$P_{\text{out}}(S_v, H_d) = \Pr\left(\sum_{i=1}^{S_v}\phi'_{i,v,s}\psi_{i,v} + \sum_{i=1}^{H_d}\phi'_{i,d,h}\psi_{i,d} > 1\right). \quad (17)$$

In order to compare with hard handoff, the voice capacity is normalized as

$$C_v = \left(1 - \frac{P_{\text{soft},v}}{2}\right)\max[S_v : P_{\text{out}}(S_v, H_d) \leq \delta] = \max[H_v : P_{\text{out}}(S_v, H_d) \leq \delta]. \quad (18)$$

4. Numerical Results

For numerical examples, let us consider the cellular layout as shown in Fig. 1. Then, by symmetry, the relative position of mobiles and bases in the center cell is the same throughout the cell as for the shaded triangle of Fig. 1 [8]. For each set of mobiles uniformly distributed on the triangle, P_{out}, P_{soft}, and C_v are evaluated.

The nominal parameter values used herein are listed in Table 1 except where otherwise specified. According to [14], the value of φ can be selected between 0 and 0.9. We use 0.5 as the nominal value of φ. We follow [15] for the values of the required E_b/N_0 of voice and data (γ_v and γ_d). It is assumed that voice and data traffics use the same threshold level ($\epsilon = \epsilon_v = \epsilon_d$). As shown in (1), (7), (13), and (17), we need the random variables λ and ψ to obtain the outage probability P_{out}. In this section, we use a simulation method to generate

Table 1 Parameter values.

Parameter	Value
bandwidth (B)	5 MHz
voice activity factor (μ_v)	0.4
data activity factor (μ_d)	0.015
number of data mobile (H_d)	10
voice information rate (R_v)	16 kbps
data information rate (R_d)	384 kbps
required E_b/N_0 of voice (γ_v)	7 dB
required E_b/N_0 of data (γ_d)	6 dB
traffic power ratio (β)	0.8
path loss exponent (ω)	4
number of cells (M)	19
orthogonality factor (φ)	0.5
standard deviation of λ (σ)	8

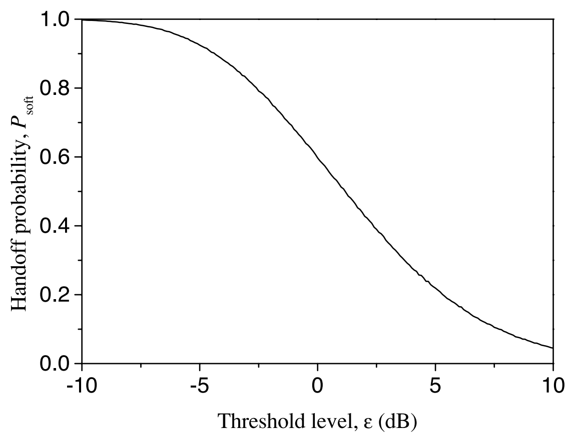

Fig. 2 Relation between the threshold level and the soft handoff probability.

the random variables λ and ψ, and to get P_{out}.

To evaluate C_v, we need additional parameter P_{soft}, which also can be obtained by simulation. The relation between the handoff threshold level ϵ and the handoff probability P_{soft} is shown in Fig. 2. As the threshold level increases, P_{soft} decreases and the system becomes more similar to hard handoff.

The outage probability of soft handoff with various values of threshold level ϵ is shown in Fig. 3. Irrespective of ϵ, the outage probability increases as the number of voice mobiles increases. From Fig. 3, we can estimate the system capacity for given δ. Recall that the capacity is the maximum of H_v that satisfies $P_{\text{out}} \leq \delta$. When δ is small (less than around 0.01. for example, see the dotted line in Fig. 3, which indicates $\delta = 0.007$), the capacity increases as the threshold level decreases. This is because the gain factor with soft handoff over hard handoff outweighs the loss factor, and soft handoff shows higher capacity than hard handoff. For large values of δ (more than around 0.01. for example, see the dash line in Fig. 3, which indicates $\delta = 0.02$), the capacity increases as ϵ increases. This is because the loss factor outweighs the gain factor and hard handoff shows higher capacity than soft handoff. Note that, because the outage probability defined in this paper is

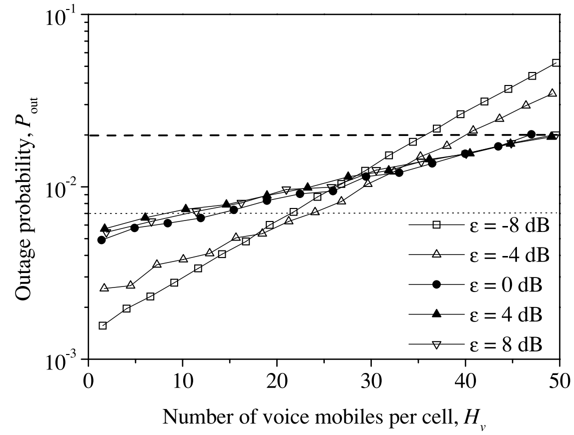

Fig. 3 The effect of threshold level on capacity with soft handoff.

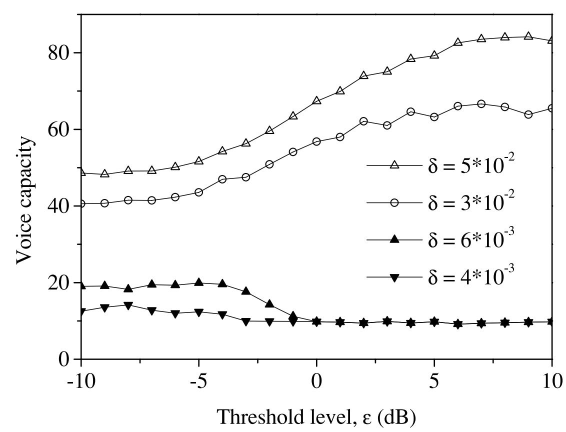

Fig. 4 Relation between the threshold level and the voice capacity.

pessimistic bound as noted in Sect. 2, the range of δ between 0.01 and 0.05 is desirable in practice.

The voice capacity of soft handoff with various values of δ is shown in Fig. 4. When δ is greater than 0.01, as the threshold level increases the voice capacity increases. When δ is less than 0.01, as the threshold level increases the voice capacity decreases. This trend matches with the result in [13] where the capacity increases or decreases depending on the handoff area and the power assignment.

The outage probabilities of each handoff method are compared in Fig. 5. The soft handoff shows the highest outage probability, which results in the lowest capacity. It is because the loss factor outweighs the gain factor. The hard handoff shows the lowest outage probability, which results in the highest capacity. From the viewpoint of capacity, the hard handoff is the best method. On the other hand, as well known, the soft handoff provides the lower call drop rate than any other handoff strategies. The proposed method is a compromise between the soft and hard handoff strategies. Thus, the improvement of the proposed method

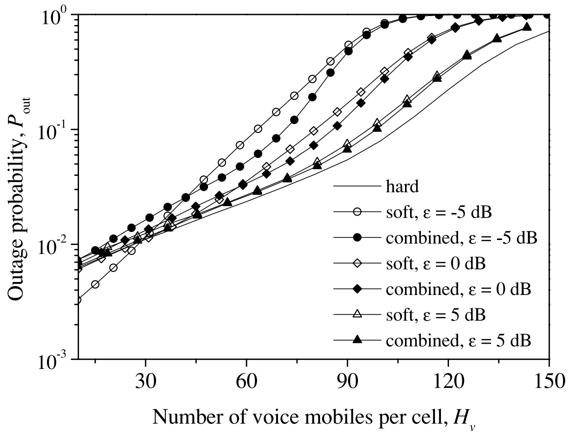

Fig. 5 Relation between the outage probability and the handoff method.

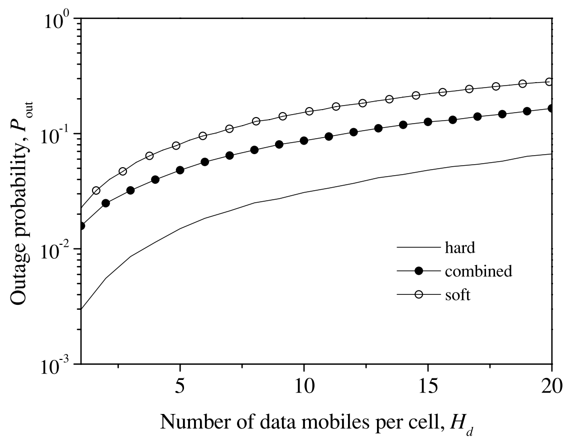

Fig. 6 Effect of data traffic on the outage probability.

over the soft handoff is the increased capacity while maintaining the QoS for voice traffic comparable to that of the soft handoff. This capacity improvement becomes larger as the value of ϵ decreases. Note that as the value of ϵ decreases, QoS of voice traffic becomes better because more mobiles enjoy the advantage of soft handoff. In Fig. 5, in case of $P_{\mathrm{out}} = 0.05$ and $\epsilon = -5\,\mathrm{dB}$, the voice capacity of soft handoff is 52 and that of the proposed combined handoff is 60. The capacity improvement is about 15%.

The effect of data traffic on the outage probability is shown in Fig. 6. The parameter values of ϵ and H_v are $-5\,\mathrm{dB}$ and 70, respectively. As the number of data mobiles (H_d) increases, the interference increases and the outage probability increases. As the required outage probability (δ) increases, the capacity improvement of the proposed method over the soft handoff gets larger.

5. Conclusions

With the emergence of asymmetric wireless data services, the forward link performance is becoming increasingly important. In the practical operational range, soft handoff lowers the call dropping rate during handoff, but can reduce the forward link capacity in CDMA systems.

We have considered a combination of soft and hard handoff schemes offering the merit of soft handoff for voice services and providing high capacity of hard handoff for data services. The performance of the combined handoff scheme has been evaluated. The results show that the combined scheme leads to better performance. The results in this paper can be used as a guideline in designing and operating the radio network of CDMA systems supporting multimedia services.

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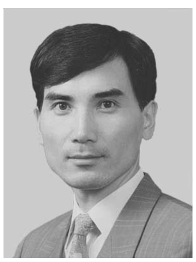

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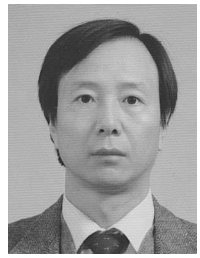

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