An Integrated Approach for Performance Modeling and Evaluation of Soft Handoff in CDMA Mobile Cellular Systems

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Abstract

In CDMA mobile cellular networks, wireless quality is improved by soft handoff techniques. However, it requires to hold multiple channels of cells, which is likely to increase call blocking at wired channels. It is therefore necessary to consider the entire system including the wired and wireless portions of CDMA mobile cellular systems for investigating an effectiveness of the soft handoff. For this, we develop an analytical method to derive blocking and forced termination probabilities as performance measures for wired channels, and outage probability for wireless ones. Through numerical examples, we evaluate the effects of the size of the soft handoff region. The effect of call control is also shown to reduce total interference on wireless channels.

1 Introduction

In CDMA mobile cellular systems, MSs (Mobile Stations) can simultaneously connect with multiple BSs (Base Stations) by a soft handoff technique. Soft handoff has following advantages over conventional hard handoff:

- Improving the radio channel quality by virtue of the decrease of total interference power [1]
- Avoiding the interruption resulting from the connection switching and frequent connection changes (known as "ping-pong effect")

Its drawback is apparent; each MS in the soft handoff state occupies wired channels at multiple BSs. Therefore, we need to identify the influence of such a redundancy on the wired channels.

Past researches on soft handoff in CDMA have been mainly dedicated to the wireless channel quality. For example, the author in [4] evaluated the trade-off relationship between wireless quality of uplink and downlink, and proposed a way to decide the size of the soft handoff region. In [3], the authors described that introducing soft handoff causes the decrease of shadow fade margin which leads to the increment of capacity or improvement of wireless quality.

However, in those studies, the limitation by the number of wired channels at each BS is not considered. If all of wired channels of one BS have already been occupied, some MSs cannot enjoy soft handoff because of lack of wired channels. The existence of such MSs must affect wireless channel quality. One of a few exceptions can be found in [2] where the authors have evaluated blocking probability for newly generated and handoff call as the performance measure of CDMA systems to discuss the influence of soft handoff on the quality of wired channels. They also presented the call control method by using those performance measures. To evaluate the performance of the call control method, however, its effect on wireless channel quality must be considered. Only such total evaluation of the soft handoff system makes it possible to decide the meaningful system parameters.

In this paper, we evaluate the effect of the size of soft handoff region on qualities of both wired and wireless channels comprehensively. We adopt blocking probability for newly arriving calls and forced termination probability of handoff calls as performance measures of wired channels, and outage probability for wireless channel quality. We derive these performance measures by an approximate analytical method. Through numerical examples, we show the effect of the size of soft handoff region on the system performance. We also introduce one example which im-

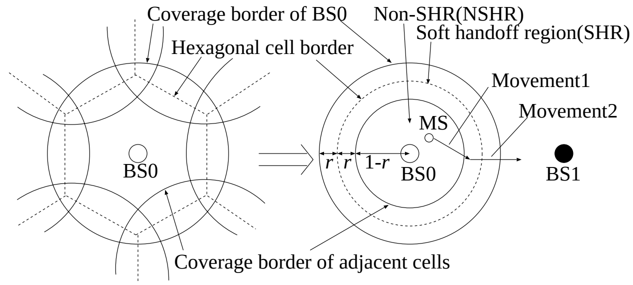

Figure 1. Approximation model of CDMA cell

proves wireless channel quality by suppressing the interference power. This shows that appropriate call control methods may improve feeling of satisfaction of users.

This paper is organized as follows. In Section 2, we explain the system model and performance measures for each wired and wireless quality. In Section 3, we propose an analysis method. Then we show numerical examples by applying our analysis method in Section 4. Finally, this paper is concluded in Section 5.

2 System Model and Performance Measures

2.1 Model of CDMA mobile cellular systems

As illustrated in Figure 1, we assume that the service area is divided into hexagonal cells, and its shape is approximated by a circle for simplicity. We also assume that MSs are uniformly distributed within the service area. As shown in Figure 1, MSs in SHR (Soft Handoff Region) can connect with BS0 and one of the adjacent BSs, but we assume that each MS cannot connect with three or more BSs at the same time. MSs in NSHR (non-SHR) can connect with BS0 only. The width of SHR is denoted by $2r$, and the NSHR radius is defined as $1 - r$ by assuming that a cell radius is always 1.

2.2 Evaluation of wired channels assignment

As described before, we evaluate the quality of wired channels in terms of blocking and forced termination probabilities. Blocking probability is defined as the probability that a newly generated call is blocked. Such an event takes place due to two reasons; a newly generated call in NSHR is blocked when there is no available channel in the nearest BS. In SHR, it is blocked when there is no available channel in both of two BSs that it can connect with. We derive blocking probability by calculating a weighted average of blocking probability in each region.

When a MS leaves a current cell, and find no available wired channel in the cells which it moves into, it is terminated forcibly. In Figure 1, the MS moving towards BS1 (Movement1) gets into the soft handoff state, if there is available wired channel at BS1. The MS can keep a call if it keeps to move for BS1 (Movement2). On the other hand, if there is no available wired channel at BS1, the MS that moves for BS1 (Movement1) has only a single connection with BS0 even in SHR. The call of the MS is forcedly terminated when the MS continues moving towards BS1 (Movement2), because it does not have a connection with BS1. As another performance measure of wired quality, we introduce forced termination probability which means the probability that a call is forcedly terminated before communication itself ends because of handoff failure.

Note one assumption for simple analysis. We consider the case that one available channel generates in BS1 when a MS connects with BS0 only in SHR. In such a case, the MS cannot connect with BS1 as long as it is in the same region.

2.3 Evaluation of wireless channel quality

In this paper, we focus on the up link in examining the wireless channel quality since it is more important in investigating the effect of the soft handoff [1]. In evaluating the wireless channel quality, we consider outage probability which is defined as the probability that the signal-to-interference ratio (SIR) is less than the threshold level realizing adequate transmission quality [5]. In the CDMA system, outage probability can appropriately evaluate wireless quality because SIR directly determines BER (Bit Error Rate). We assume that perfect power control is realized such that power from MS is steadily received at BS.

3 The Analysis Method

Here, we show our analysis method to obtain performance measures which we have explained in previous section. We first consider wired channels and derive blocking probability and forced termination probability. By the analysis, we will obtain the numbers of MSs in SHR and NSHR in steady state. We will then derive interference power, and obtain outage probability.

3.1 Blocking probability and forced termination probability

We assume that generation of new calls follows the Poisson process, and the arrival rate per one cell is denoted as λ. Call holding time and residual time per one cell are assumed to follow the exponential distribution, and denoted as $1/\mu$, $1/\mu_c$ respectively. Then, residual time in NSHR and SHR, $1/\mu_s$ and $1/\mu_m$, also follow exponential distribution. Those can be calculated from $1/\mu_c$ (See Appendix A of [6]).

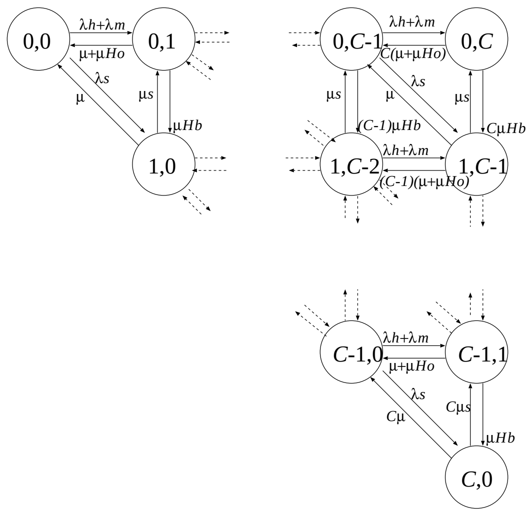

Figure 2. State transition probability for occupied wired channels for SHR and NSHR

We assume that MSs spread uniformly in the system. Therefore, we can derive performance measures by focusing on one cell. In the target cell, we denote the number of calls in NSHR as n_s, and in SHR as n_m. The state of occupied wired channels is then denoted as (n_s, n_m), and the steady state probability of (n_s, n_m) is denoted as $p(n_s, n_m)$.

From call arrival rate per one cell λ, the call arrival rate in NSHR and SHR, λ_s and λ_m, are calculated by considering area of each region.

$$\lambda_s = (1-r)^2\lambda, \;\; \lambda_m = 4r\lambda \tag{1}$$

When MSs in SHR move out from the region, they are assumed to move into NSHR with the probability b_k (See Appendix B of [6]). With this assumption, the probabilities that MSs in SHR move out to NSHR, μ_{Hb}, and to out of the target cell, μ_{Ho} are given as follows.

$$\mu_{Hb} = b_k\mu_m, \;\; \mu_{Ho} = (1-b_k)\mu_m \tag{2}$$

In steady state, the call arrival rate from other cells to the target cell and departure rate from the target cell to other cells are assumed to be equivalent. Therefore, we can calculate λ_h which means the call arrival rate from other cells to SHR of the target cell, as

$$\lambda_h = \sum_{n_s=0}^{C}\sum_{j=n_m}^{C-n_s} n_m \cdot \mu_{Ho} \cdot p(n_s, n_m) \tag{3}$$

With these assumptions and calculations, we can obtain the state transition probabilities (see Figure 2). This transition can be expressed by following equilibrium state equation.

$$\begin{aligned}
&\{n_s(\mu+\mu_s) + n_m(\mu+\mu_{Hb}+\mu_{Ho})\\
&+\lambda_m+\lambda_h+\lambda_s\}p(n_s,n_m)\\
&=\lambda_s p(n_s-1,n_m) + (\lambda_m+\lambda_h)p(n_s,n_m-1)\\
&\;\;+(n_m+1)\mu_{Hb}p(n_s-1,n_m+1)\\
&\;\;+(n_s+1)\mu_s p(n_s+1,n_m-1)\\
&\;\;+(n_s+1)\mu p(n_s+1,n_m)1_{\{n_s+n_m<C\}}\\
&\;\;+(n_m+1)(\mu+\mu_{Ho})p(n_s,n_m+1)1_{\{n_s+n_m<C\}}
\end{aligned} \tag{4}$$

The steady state probability can then be obtained by applying the normalization condition;

$$\sum_{n_s=0}^{C}\sum_{n_m=0}^{C-n_s} p(n_s,n_m) = 1 \tag{5}$$

However, as shown in Equation 3, call arrival rate from other cells depends on the steady state probabilities. Therefore, by repeating calculations, we can obtain its convergence as the steady state probabilities. The probability that the target cell has no available channels, p_f, is given by the sum of the probabilities of states with $n_s + n_m = C$, i.e.,

$$p_f = \sum_{(n_s,n_m);n_s+n_m=C} p(n_s,n_m) \tag{6}$$

To derive the blocking probability of users, we consider the users within hexagonal cell border of one cell (Figure 1). The call arrival rate in SHR within the border is given by $\lambda - \lambda_s$. Then, blocking probability P_B can be obtained by calculating a weighted average;

$$P_B = \lambda_s p_f + (\lambda-\lambda_s)p_f^2 \tag{7}$$

By letting the probability that users go out from coverage border (Figure 1) be μ_{cover}, the probability that users go out from coverage border before they terminate their call is given by $\left(\frac{\mu_{cover}}{\mu+\mu_{cover}}\right)$. Then, the forced termination probability is obtained by

$$P_T = \sum_{i=0}^{\infty}\left(\frac{\mu_{cover}}{\mu+\mu_{cover}}\right)^{i+1}(1-p_f)^i p_f \tag{8}$$

Note that derivation of μ_{cover} is found in [6].

3.2 Calculation of outage probability

Here, we show the analysis method of outage probability that exhibits wireless channel quality. It can be obtained by calculating interference power that a BS receives from MSs.

We assume that the power that each MS radiates (denoted by E_{trans}) is ideally controlled and be received at

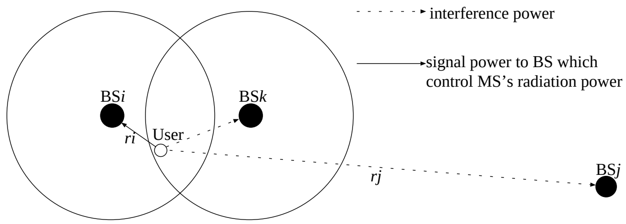

Figure 3. Interference power from the user in soft handoff state

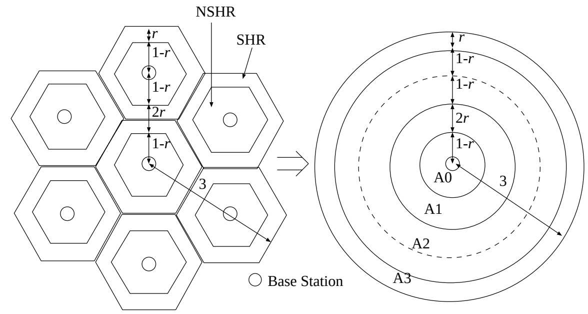

Figure 4. Approximation model for calculating outage probability

same power, E_s, at the BS. Furthermore, let us introduce I_{BS} to represent the interference power that the BS receives from all MSs.

In Figure 3, the user is in the soft handoff state, and connects with BS_i and BS_k. Then we assume that attenuation to BS_i is smaller than BS_k including distance and shadowing effect. That is, the required power from BS_i is smaller for the user than BS_k. As described before, the user can keep communication as long as it can connect with at least one BS. Therefore, the radiation power of the user is enough if it satisfies the required power from BS_i. To derive the radiation power for the user, we further introduce γ denoting the attenuation which is in inverse proportion to the distance [1]. Moreover, ζ_i represents the attenuation by the shadowing which follows the regular distribution. ζ_i has two parts; the one is a common element for whole system (denoted by ξ) and the other is the element dependent on each BS (ξ_i). It is then given by

$$\zeta_i = \frac{1}{\sqrt{2}}\xi + \frac{1}{\sqrt{2}}\xi_i \tag{9}$$

The radiation power for the user, E_{trans}, is given by using the above quantities as;

$$E_{trans} = E_s \cdot r_i^{\gamma} 10^{\zeta_i/10} \tag{10}$$

With these equations, interference power that BS_j receives from the user is calculated as;

$$I_{BSj} = \frac{E_{trans}}{r_j^{\gamma} 10^{\zeta_i/10}} = E_s \left(\frac{r_i}{r_j}\right)^{\gamma} 10^{\frac{\xi_i - \xi_j}{10\sqrt{2}}} \tag{11}$$

We introduce another assumption to calculate outage probability. If we want to take account of outage probability correctly, we should calculate interference power from all MSs in the service area. However, interference power from MSs which is far from the target BS can be ignored because of attenuation by the distance. Therefore, we approximately obtain the outage probability by considering interference power from MSs in the target cell and the neighbor cells. For simple analysis, we approximate these cells are circular area as shown in Figure 4. We then calculate interference power from MSs in each region, from A0 to A3. The mean of the interference power from each MS in NSHR can be calculated as follows.

$$E[Is] = E_s \left(\frac{r_i}{r_j}\right)^{\gamma} E[10^{\frac{\xi_i - \xi_j}{10\sqrt{2}}}] \tag{12}$$

For MSs in SHR, it is given by;

$$\begin{aligned} E[Im] &= E_s \left(\frac{r_i}{r_j}\right)^{\gamma} E[10^{\frac{(\xi_i - \xi_j)}{10\sqrt{2}}}] \\ &\quad \cdot P(r_i^{\gamma} 10^{\zeta_i/10} < r_k^{\gamma} 10^{\zeta_k/10}) \\ &+ E_s \left(\frac{r_k}{r_j}\right)^{\gamma} E[10^{\frac{(\xi_k - \xi_j)}{10\sqrt{2}}}] \\ &\quad \cdot P(r_i^{\gamma} 10^{\zeta_i/10} > r_k^{\gamma} 10^{\zeta_k/10}) \end{aligned} \tag{13}$$

The mean interference power from all MSs in the target area is given by summing means of those from all MSs, because interference power from each MS are independent. In a similar manner, the variance is also calculated. The mean number of users in NSHR, N_s, is obtained by using the steady state probability, which was derived in Subsection 3.1.

$$N_s = \sum_{n_s=0}^{C} \sum_{n_m=0}^{C-n_s} n_s p(n_s, n_m) \tag{14}$$

The mean number of users in SHR, N_m, is also obtained in a similar way. By multiplying the mean number of users by the area of region A0 (and A1, A2 and A3), we can obtain the average number of MSs in each region. SIR at the target BS is denoted as follows.

$$SIR = \frac{G_p E_b}{I_{BS}} \tag{15}$$

Here, G_p means process gain at BSs. By denoting required SIR as SIR_{req} and mean and variance of interference power from all MSs as $E[I_{BS}], Var[I_{BS}]$, outage

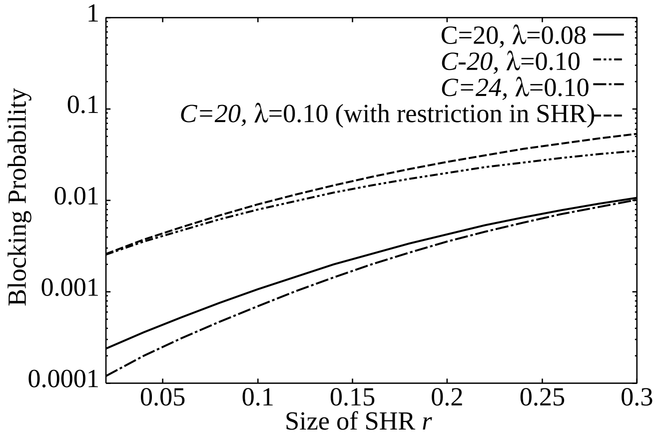

Figure 5. The effect of size of SHR on blocking probability

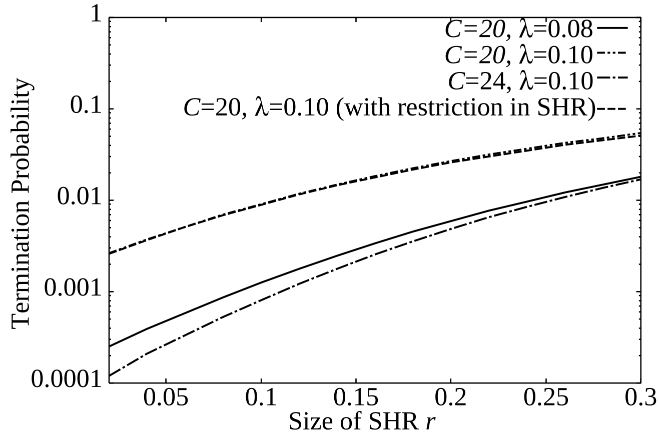

Figure 6. The effect of size of SHR on forced termination probability

probability $Pout$ is obtained as follows.

$$\begin{aligned} Pout &= P\left(I_{BS} > \frac{Gp}{SIR_{req}}\right) \\ &= Q\left(\frac{\frac{G_p}{SIR_{req}} - E[I_{BS}]}{\sqrt{Var[I_{BS}]}}\right) \end{aligned} \quad (16)$$

4 Numerical examples and discussions

In this section, we demonstrate the applicability of our method. An arrival rate of the new calls at each cell is denoted as λ. The number of wired channels of BS is denoted as C. System parameters are summarized in Table 1.

We plot blocking and forced termination probabilities against the size of SHR, r, in Figures 5 and 6, respectively. Blocking and forced termination probabilities are increased as r gets larger. It is natural because the number of available wired channels becomes short as more MSs are allowed to be moved into the soft handoff state.

The corresponding outage probabilities are shown in Figure 7. Outage probability is first improved against increased r. However, it is degraded when exceeding some value. It is because the SHR size gives different influences on outage probability. Due to the soft handoff, the interference power can be decreased. It contributes the decrease of outage probability and the effect is dominant when r is small. However, as r becomes larger, MSs connecting with single BS in SHR (which have failed to connect with another BS) is increased due to lack of the available wired channels. Those MSs must send the signal with stronger power to keep the connection with far BS. Then, outage probability becomes worse against the larger r.

Table 1. System parameters

number of wired channels per a BS	C	20-24
call arrival rate	λ	0.08-0.10
mean call holding time	$1/\mu$	100
mean residual time	$1/\mu_c$	100
process gain	ν	0.375
required SIR	SIR_{req}	7dB

By comparing two lines ($\lambda = 0.08$ and 0.10), we can also observe that the increased load makes the performance worse. Then, increasing the number of wired channels can improve the performance again as expected. See the lines for $C = 24$ in three figures. One remarkable point observed in the figure is that the optimal value of r to minimize outage probability is shifted. Thus, we need to seek out the optimal value of the size of SHR by some appropriate method such as ours.

If we look at the results more carefully, we can find another approach without more wired channels. By changing the load from $\lambda = 0.08$ to 0.10 (for $C = 20$), the performance (blocking and forced termination probabilities and outage probability) was degraded. It is because as the traffic load becomes high and the number of available wired channels becomes little, MSs are likely to fail to move into the soft handoff state within SHR. Then those MSs send strong interference power to BSs because they must keep connection with far BS. It results in that outage probability is degraded by increased SIR values. It suggests that we can expect performance improvement by following method. In Figure 8, MS1 has connections with both BS0 and BS1,

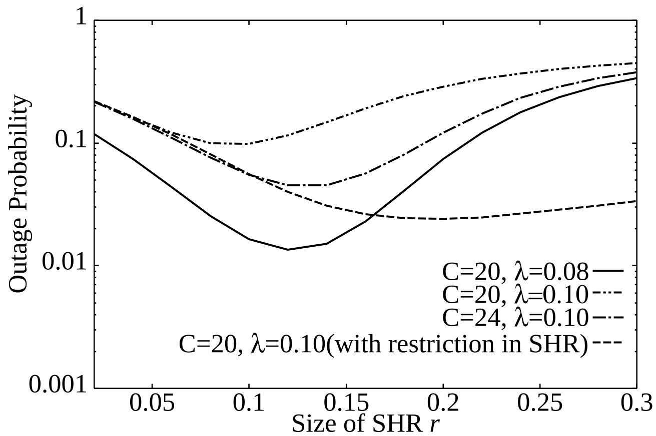

Figure 7. The effect of size of SHR on outage probability

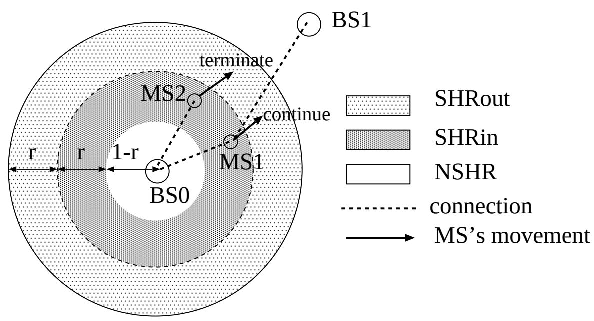

Figure 8. Restriction of MSs in SHR for wireless quality improvement

and MS2 has only one connection with BS0. When MS1 moves to SHRout, it can keep connections with both BS0 and BS1. However, when MS2 moves to SHRout, its connection with BS0 is terminated forcibly because it radiates strong power and degrades wireless quality of other users. The results are also shown in the figures with the label "with restriction in SHR". Here, we set $C = 20$ and $\lambda = 0.10$. In our method, blocking and forced termination probabilities are not degraded, while outage probability can much be improved.

5 Conclusion

In this paper, we have proposed evaluation method of soft handoff in CDMA mobile cellular systems. We have adopted blocking and forced termination probability as performance measures of wired channels, and outage probability as for wireless channels. Then, we have calculated these performance measures by analytical method.

We have clarified the effect of the width of soft handoff region and the number of wired channels at a BS on these performance measures, by showing some numerical examples obtained from our analytical method.

From our results, it is apparent that adjusting system parameters by considering both wired and wireless quality is needed for system design. This integrated evaluation is necessary to control a system after the operation of the system starts.

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