## Master's Thesis

Title

# An Integrated Evaluation of Qualities of Wired and Wireless Channels with Consideration of Soft Handoff in CDMA Cellular Systems

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February 14th, 2001

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## Abstract

In CDMA mobile cellular systems, 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 systems for investigating an effectiveness of the soft handoff. The effect of interference power from mobile stations that are not in the soft handoff is also important to be investigated. In this paper, we propose an integrated evaluation method of qualities of wired and wireless channels, and gives an analysis method which can incorporate the above-mentioned problems. In the analysis, we model three-way soft handoff which has not been considered in past researches. We also show the effect of a call admission control on wireless quality. Moreover, we investigate the effect of soft handoff in IMT-2000. In IMT-2000, the demand for data communication would be increased according to an explosive demand on the Internet accesses. It means that the performance of the download link would become more important. A soft handoff technique is effective on the uplink in general because it suppresses the interference power from MSs. However, more than one BS must send signals for MSs during the soft handoff state. It implies that the interference power for downlink is also increased. Taking those facts in mind, we investigate the soft handoff in IMT-2000 through simulation studies. Our finding is that an improvement by soft handoff technique can be found, but it depends on the network configuration and the traffic load. Thus a careful design of the soft handoff is necessary for it to be powerful for the high-quality data communications.

## Keywords

CDMA (Code Division Multiple Access)
soft handoff
wired channel
wireless channel
IMT-2000 (International Mobile Telecommunications-2000)

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# 1 Introduction

In CDMA mobile cellular systems, mobile stations (MSs) can simultaneously connect with multiple base stations (BSs) by soft handoff techniques. Soft handoff has several advantages over hard handoff; It can avoid the interruption resulting from the frequent connection switching. Moreover, an improvement of the radio channel quality by decreasing interference power can be expected. However, each MS in soft handoff state occupies wired channels at multiple BSs, and we need to identify the influence of such a redundancy on the wired channels.

Past researches on CDMA soft handoff are mainly dedicated to the quality of wireless channels. In [1], Seïte evaluated the tradeoff relationship between radio channel quality of uplink and downlink, and proposed a way to decide an appropriate size of the soft handoff region. Chopra et al. [2] showed that introducing soft handoff causes the decrease of shadow fade margin, which leads to the increment of capacity or improvement of quality of wireless channels. As an exception, Paik and Jin [3] evaluated blocking probabilities for newly generated and handoff calls as the performance measure of CDMA systems, and discussed the influence of soft handoff on the quality of wired channels. They also presented a call admission control method by considering those performance measures.

In those researches, however, either wired or wireless channel performance was examined separately, in spite that it is necessary to evaluate the influence of soft handoff on both wired and wireless channel performance in an integrated manner for the design of efficient and high quality networks. It is because system parameters, such as the size of soft handoff region and the number of wired channels, affect qualities of both wired and wireless channels. For example, a larger soft handoff region makes more MSs be in soft handoff state and improves quality of wireless channels, although it makes more MSs consume redundant wired channels in multiple BSs. This may cause deterioration of blocking probabilities for newly generated and handoff calls. This limitation may also deteriorate quality of wireless channels. As will be shown in later, this deterioration results from the interference power from MSs which cannot enjoy soft handoff because of lack of wired channels.

In this paper, we show the necessity of considering the entire system including the wired and wireless portions of systems for investigating an effectiveness of soft handoff. In our research, we consider the number of wired channels and the size of soft handoff region as system parameters, because it is an important cost factor for system operators. In CDMA systems, the number of MSs, which can communicate with one BS simultaneously, is limited by interference power. Therefore, there exists capacity limitation, and we call this capacity as wireless capacity. This wireless capacity can also affect qualities of both wired and wireless channels. To clarify the effect of wireless capacity, we should consider the interference power from other cells. It is different from the effect of wired capacity which limits the number of wired channels in one cell. On the other hand, wireless capacity is affected by the interference power that one BS receives from all the other MSs in a whole service area. Therefore, an influence from other cells should be explicitly considered. In order to show the necessity of integrated evaluation of qualities of both wired and wireless channels, we first evaluate the effect of the limitation of the number of wired channels.

For that purpose, we adopt an analysis method which takes three-way soft handoff into consideration. In past researches, it was assumed that MSs can simultaneously connect with at most two BSs. In a practical environment, however, MSs can connect with more than two BSs as realized in IS-95 systems. Actually, the three-way connection influences quality of both wired and wireless channels, because more wired channels are occupied. Therefore, we newly develop an analysis method allowing that MSs can connect with three BSs simultaneously.

Moreover, we investigate an effect of a call admission control which is introduced for improving handoff refused probabilities [3]. In [3], the effect of such a control on only quality of wired channel was investigated. On the contrary, we will show that through an integrated evaluation method, such a call admission control affects not only quality of wired channels but also quality of wireless channels.

In the above, we mainly consider voice communication and its quality. However, in IMT-2000, data communications will play a leading part of mobile communications. This shift may change the significance of soft handoff. The reason is due to an increase of downlink traffic in data communications such as Web browsing. In general, soft handoff is a powerful technique for uplink communication because it suppresses an interference power from MSs. However, in downlink communication, more than one BS must send signal for MSs in the soft handoff state. Therefore, the interference power of the downlink is likely to increase. For that reason, in CDMA system with soft handoff techniques, downlink quality of MSs not in soft handoff state may deteriorate when comparing with the system without soft handoff. However, an opposite observation is also possible. Downlink quality of MSs in soft handoff state may be improved by the effect of maximal ratio combining, which is a technique summing the demodulation results of groups of signals from different BSs. Moreover, in data communications, there is a retransmission mechanism. Therefore, the performance may not directly reflect the difference of quality of wireless channels. By considering those features of soft handoff in downlink communications, the purpose of our research in this thesis is to clarify the effect of soft handoff in IMT-2000. In our study, we use a simulation technique to investigate a dynamic behavior of MSs in handoff. In our simulation, we mainly consider an influence of network load and soft handoff margin.

This paper is organized as follows. In Section 2, we explain the analysis method considering three-way soft handoff, and show some numerical examples obtained by applying our analysis method. In Section 3, we identify the effect of soft handoff in IMT-2000. Finally, this thesis is concluded with several remaining research topics in Section 4.

# 2 An Integrated Evaluation of Qualities of Wired and Wireless Channels with Consideration on Soft Handoff

## 2.1 System Model and Performance Measures

### 2.1.1 Model of CDMA mobile cellular systems

We assume that service area is divided into hexagonal cells, and MSs spread on the system uniformly. In Figure 1, each circle around BSs is the boundary that MSs can connect with BSs. MSs in the single connection region can connect with only BS0. MSs in two-way connection region can connect with not only BS0 but also the nearest BS that is in the adjacent cell. Moreover, MSs in the three-way connection region can connect with BS0 and two nearest BSs in the adjacent cells. We assume that the distance between two BSs

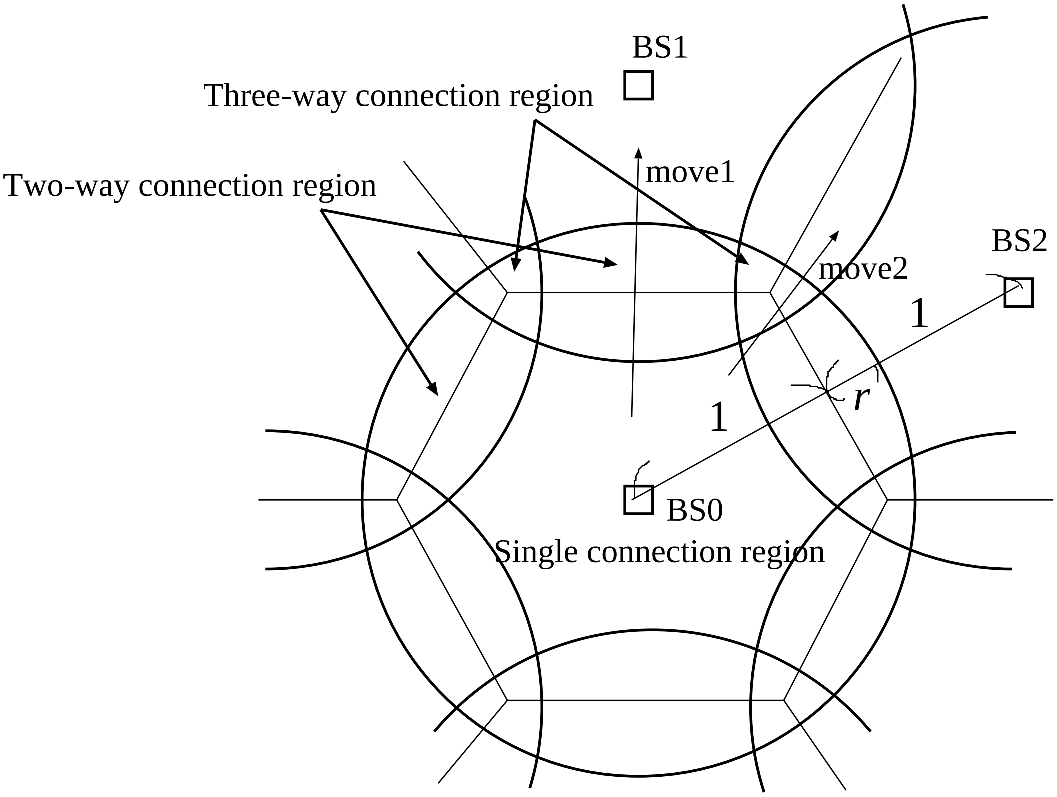

Figure 1: Regions in our model

is two, and MSs can connect with a BS if the distance between them is $1 + r$ or less.

### 2.1.2 Evaluation of wired channels assignment

We evaluate the assignment method of wired channels in terms of blocking probability for newly generated calls and handoff refused probability. A newly generated call in each region requests channels to every BSs that it can connect with. The call generated in the single connection region requests a channel to only one BS. On the other hand, the call generated in three-way connection region requests channels to all of three BSs. If there is no available wired channel in every BSs, the call is blocked. We call the probability that a newly generated call is blocked as *blocking probability*, and adopt it for one of performance measures to measure quality of wired channels.

When the MS leaves current cell, and it finds there is no available wired channel in the cell that it moves into, it is terminated forcibly. In Figure 1, the MS which moves into a single connection region (*move1*) is terminated after it loses the connection with BS0, if there is no available wired channel at BS1. The MS which moving into two-way connection region (*move2*) can connect with two BSs, BS1 and BS2, after leaving the current cell. In this case, it is terminated only when there is no available channel in both two BSs. We call the probability that a handoff call is terminated after it leaves the current cell as *handoff refused probability*, which is another performance measure of quality of wired channels.

Note that the MS may be in a single connection state even if it is in the soft handoff region, but some BSs have no available channels. We assume that calls which cannot be in soft handoff state keep the same state as long as they are in the same region, even if available channels are generated in one of BSs which they do not connect with. That is, the connection state can change at only a boundary of each region.

### 2.1.3 Evaluation of quality of wireless channels

We focus on the uplink to evaluate quality of wireless channels. This is because the soft handoff mainly affects uplink quality of wireless channels [4, 5]. As a performance measure of quality of wireless channels, we adopt interference power that each BS receives. For the MS connecting with the BS, the power that the BS receives from other MSs becomes interference power for that MS. In CDMA systems, quality of wireless channels of the MS deteriorates as the interference power becomes stronger, because quality of wireless channels of a MS is affected by the ratio of the signal power from it to interference power from other MSs. We assume that MSs are perfectly power-controlled. That is, BSs can always receive signals from accommodating MSs at same power. Then, we can evaluate quality of wireless channels of a MS by interference power from other MSs.

## 2.2 Analysis Method Considering Three-way Soft Handoff

We now present our analysis method to obtain performance measures which we explained in the previous section. First, we focus on wired channels to derive blocking probability and handoff refused probability. Also, we obtain the number of MSs in each area in steady state. Then, we will derive me interference power. We determine these performance measures by focusing on one cell by assuming that MSs spread uniformly in the system. In the target cell, the number of calls in the single connection region is denoted as $n_1$, and the number of calls in two-way and three-way connection regions are $n_2$ and $n_3$, respectively. The state of occupied wired channels is then expressed as ($n_1$, $n_2$, $n_3$). Its steady state probability is represented as $p(n_1, n_2, n_3)$. We assume that the generation of new calls follows the Poisson process, and the arrival rate per unit cell (the hexagonal cell in Figure 1) is denoted as $\lambda$. Call arrival rates in each region, $\lambda_1$, $\lambda_2$ and $\lambda_3$, can be obtained according to the area of each region, $A_1$, $A_2$ and $A_3$ (single connection, two-way

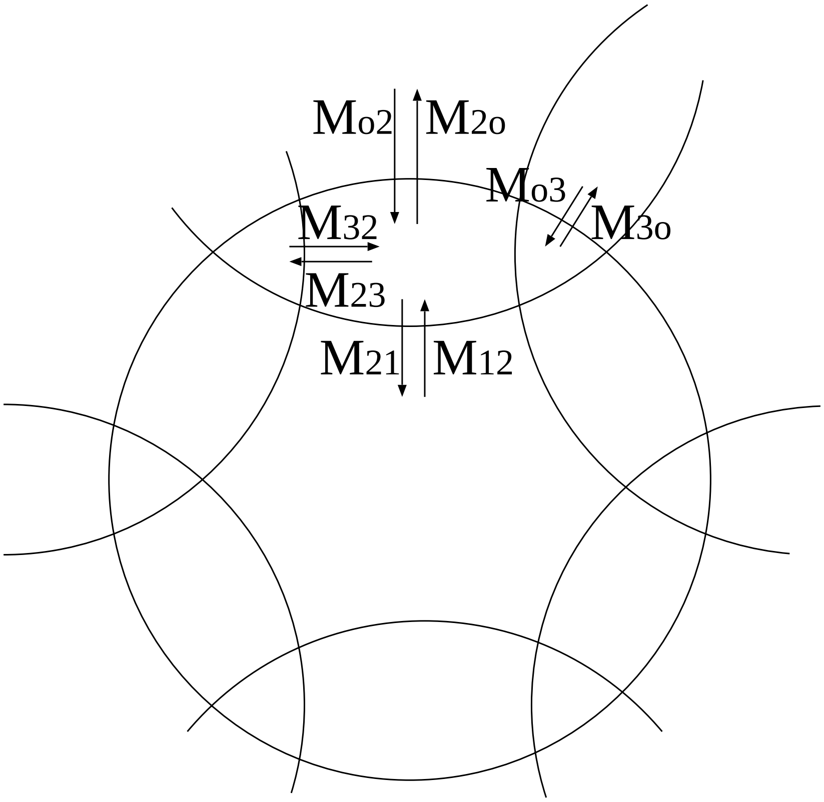

Figure 2: Transition probability for MSs between each regions

connection and three-way connection regions) as,

$$\lambda_i = \frac{A_i}{2\sqrt{3}}\lambda \ , \ i = 1, 2, 3 \tag{1}$$

We also assume that call holding time and residual time of MSs in each region follow the exponential distribution. A mean call holding time is given by $1/\mu$, and we will derive the mean residual time in the next subsection.

### 2.2.1 Derivation of mean residual time of MSs

We first show a determination method of a mean residual time of MSs in each region. MSs are assumed to move at a fixed speed and never change its direction for simplicity. The mean residual time includes both cases of newly generated calls and handoff calls. Therefore it is necessary to calculate a weighted average by considering the number of both calls. However, we only consider the mean residual time of newly generated calls for easy calculation, because those are dominant factors in determining the performance when cell movement do not occur frequently. We assume that calls are generated uniformly in the cell and MSs travel every direction with same probability. We then calculate the distance from a generation point of a call to the boundary of the region. By calculating this distance for all coordinates and all directions, we can obtain the mean traveling distance of MSs, $d_1$. The mean distance in the single connection region $1/\mu_1$ is calculated as follows.

$$1/\mu_1 = d_1/s \tag{2}$$

An average speed of MSs, $s$, is calculated by obtaining the mean traveling distance for unit cell $d_b$ and the mean residual time in the unit cell $1/\mu_c$. In similar way, we can obtain mean residual times $1/\mu_2$ and $1/\mu_3$ for two-way and three-way connection regions.

Concerning MSs in the two-way connection region, they can move into both single and three-way connection regions. For calculating a distance of each coordinate to each direction, we count the numbers of MSs to regions 1 and 3, $N_{21}$ and $N_{23}$, respectively. We also calculate the mean distance for each region, $d_{21}$ or $d_{23}$. The probability that MSs move into each region is in proportion to the number of MSs, and in inverse proportion to distance because we assume that MSs travel at steady speed. Considering these facts, the probability that MSs move into single connection region $R_1$ is obtained as follows.

$$R_1 = \frac{N_{21}d_{23}}{N_{21}d_{23} + N_{23}d_{21}} \tag{3}$$

Then, the probability that MSs move into three-way connection region is expressed as $1 - R_1$. Finally, the probability that MSs move away from two-way connection region is denoted as $\mu_2$, which is a reciprocal of the mean residual time. Therefore the probability that MSs in the two-way connection region move into single connection region and three-way connection region (denoted as $\mu_{21}$ and $\mu_{23}$, respectively) are expressed as follows.

$$\mu_{21} = R_1\mu_2 \tag{4}$$

$$\mu_{23} = (1 - R_1)\mu_2 \tag{5}$$

### 2.2.2 Blocking probability and handoff refused probability

We next obtain the number of MSs in each region in steady state by considering state transition probabilities, where the state for the numbers of occupied channels in each region is expressed as $(n_1,\ n_2,\ n_3)$. State transitions occur at generation of calls, termination of calls and movement of MSs between cells. As to the movement of MSs, there are eight cases as illustrated in Figure 2. Each transition probability is listed below.

$$M_{12} = n_1\mu_1$$

$$M_{21} = (1/2)n_2\mu_{21}$$

$$M_{23} = n_2\mu_{23}$$

$$M_{32} = (2/3)n_3\mu_3$$

$$M_{2o} = (1/2)n_2\mu_{21}$$

$$M_{o2} = A_{n_1}\mu_1$$

$$M_{3o} = (1/3)n_3\mu_3$$

$$M_{o3} = (1/2)A_{n_2}\mu_{21}$$

When considering the arrival of handoff calls, we assume that all cells are in steady state. We denote the mean number of MSs in single and two-way connection regions in steady state as $A_{n_1}$ and $A_{n_2}$, respectively. $A_{n_1}$ is calculated as follows.

$$A_{n_1} = \sum_{n_1=0}^{C}\sum_{n_2=0}^{C-n_1}\sum_{n_3=0}^{C-n_1-n_2} n_1 p(n_1, n_2, n_3) \tag{6}$$

$A_{n_2}$ is calculated in a similar way. Then we can obtain state transition probability to determine the equilibrium state equation as follows.

$$\{\lambda_1{+}\lambda_2{+}\lambda_3{+}(n_1{+}n_2{+}n_3)\mu{+}A_{n_1}\mu_1$$

$$+(1/2)A_{n_2}\mu_{23}{+}(1/2)n_2\mu_{21}{+}(1/3)n_3\mu_3{+}n_1\mu_1$$

$$
\begin{aligned}
&+(1/2)n_2\mu_{21}+n_2\mu_{23}+(2/3)n_3\mu_3\}p(n_1,n_2,n_3)\\
&=\lambda_1 p(n_1-1,n_2,n_3)+(\lambda_2+A_{n_1}\mu_1)p(n_1,n_2-1,n_3)\\
&+(\lambda_3+A_{n_2}\mu_{23})p(n_1,n_2,n_3-1)\\
&+(n_1+1)\mu p(n1+1,n_2,n_3)1_{\{n_1+n_2+n_3<C\}}\\
&+(n_2+1)(\mu+(1/2)\mu_{21})p(n_1,n_2+1,n_3)1_{\{n_1+n_2+n_3<C\}}\\
&+(n_3+1)(\mu+(1/3)\mu_3)p(n_1,n_2,n_3+1)1_{\{n_1+n_2+n_3<C\}}\\
&+(n_1+1)\mu_1 p(n_1+1,n_2-1,n_3)\\
&+(1/2)(n_2+1)\mu_{21}p(n_1-1,n_2+1,n_3)\\
&+(n_2+1)\mu_{23}p(n_1,n_2+1,n_3-1)\\
&+(2/3)(n_3+1)\mu_3 p(n_1,n_2-1,n_3+1) \qquad (7)
\end{aligned}
$$

Then we calculate steady state probabilities by considering the normalization condition;

$$\sum_{n_1=0}^{C}\sum_{n_2=0}^{C-n_1}\sum_{n_3=0}^{C-n_1-n_2} p(n_1,n_2,n_3)=1 \qquad (8)$$

Note that, as shown in Eq.(6), the arrival rate of handoff calls depends on steady state probabilities. Therefore we repeat the above calculations until the iteration converges. The probability that every available channels are occupied in the target cell $p_f$ is determined by collecting the case $n_1+n_2+n_3=C$, and expressed as follows.

$$p_f=\sum_{(n_1,n_2,n_3);n_1+n_2+n_3=C} p(n_1,n_2,n_3) \qquad (9)$$

The blocking probabilities of calls generated in single, two-way, three-way connection regions become $p_f$, $p_f^2$ and $p_f^3$, respectively, according to the number of BSs that they can connect with. We then calculate blocking probability in the whole service area, $P_B$, by considering weights. That is, by considering that the service area is divided by hexagonal cells (See Figure 1), $P_B$ becomes

$$P_B=\frac{\lambda_1 p_f+\frac{1}{2}\lambda_2 p_f^2+\frac{1}{3}\lambda_3 p_f^3}{\lambda} \qquad (10)$$

In what follows, we explain the calculation method of the handoff refused probability. We assume that the MS moves away the current cell and equally towards the every border. Accordingly, the ratio of the number of MSs that move into single connection region to the number of MSs that move into two-way connection region can be obtained by the ratio of circumference, which is denoted as $\theta_{T_1}/\theta_{T_2}$ of the central angles, i.e.,

$$\begin{aligned}
\theta_1 &= \cos^{-1}\frac{1}{1+r} \\
\theta_2 &= \frac{\pi}{6} \\
\frac{\theta_{T_1}}{\theta_{T_2}} &= \frac{\frac{\pi}{3}-\theta_1}{\theta_1-\theta_2}
\end{aligned}$$

Since handoff-refused probability for MSs that move into the single connection region is given by $p_f$, and $p_f^2$ for the two-way connection region, we can obtain handoff-refused probability $P_T$ by considering the weighted average as follows.

$$P_T = \frac{p_f\theta_{T_1} + p_f^2\theta_{T_2}}{\theta_{T_1}+\theta_{T_2}} \tag{11}$$

### 2.2.3 Calculation of interference power

We express the quality of wireless channels by interference power. Interference power from each user can be calculated by following [5]. In that paper, the power that each MS radiates ($E_{trans}$ in our paper) is assumed to be ideally controlled and be received with same power, $E_s$, at the BS.

In Figure 4, the user is in soft handoff state by connecting with both BS$_i$ and BS$_k$. Then we assume that attenuation to BS$_i$ is smaller than BS$_k$ including a distance attenuation and a shadowing effect. That is, the required power from BS$_i$ is smaller than that from BS$_k$. As described before, the user can keep communication as long as it connects 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

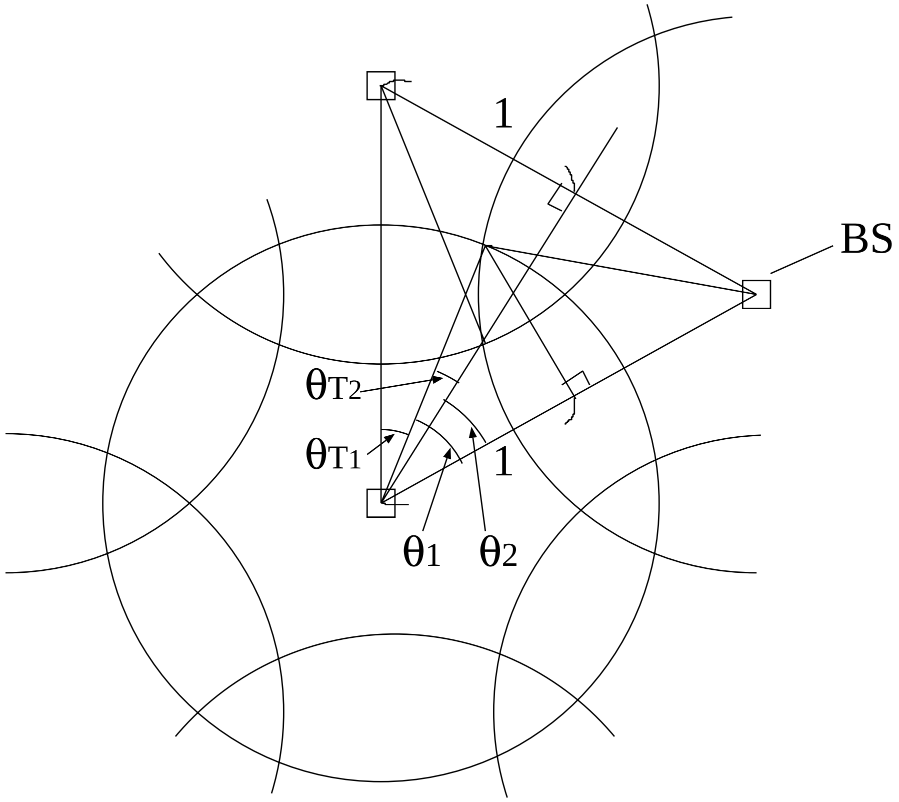

Figure 3: Transition of handoff calls

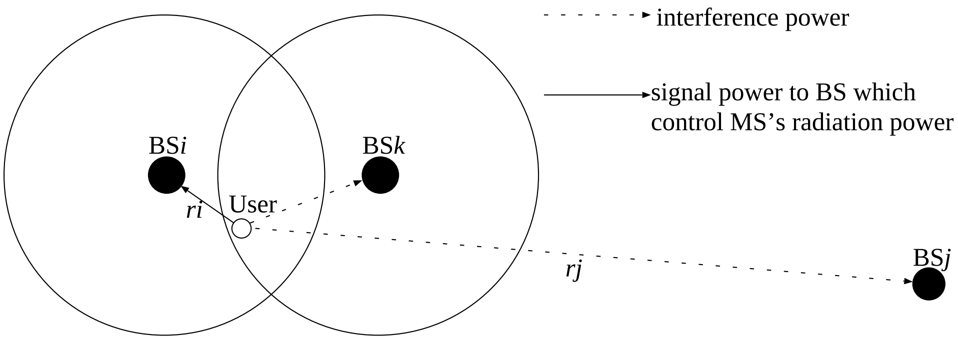

Figure 4: Interference power from the user in soft handoff state

$\gamma$, denoting the attenuation which is in inverse proportion to the distance. Moreover, $\zeta_i$ represents the attenuation by the shadowing which follows the regular distribution. $\zeta_i$ consists of two parts; the one is a common element for whole system (denoted by $\xi$) and the other is the element dependent on each BS($\xi_i$). It is then given by

$$\zeta_i = \frac{1}{\sqrt{2}}\xi + \frac{1}{\sqrt{2}}\xi_i \tag{12}$$

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

$$E_{trans} = E_s \cdot r_i^{\gamma} 10^{\zeta_i/10} \tag{13}$$

With these equations, interference power that BS$_j$ receives from the user, $I_{BSj}$, is calculated as;

$$I_{BSj} = \frac{E_{trans}}{r_j^{\gamma} 10^{\zeta_i/10}} = E_s \left(\frac{r_i}{r_j}\right)^{\gamma} 10^{\frac{\xi_i - \xi_j}{10\sqrt{2}}} \tag{14}$$

We introduce another assumption to calculate interference power that each BS receives. If we want to take account of interference power correctly, we should calculate interference power from all MSs in the service area. However, interference power from MSs which is located far from the target BS can be ignored because of attenuation by the distance. Therefore, we approximately obtain interference power by considering MSs in the target cell and the neighbor cells.

The mean interference power from the user in the two-way connection region, $E[Im]$, can be calculated as follows.

$$\begin{aligned} E[Im] &= E_s \left(\frac{r_i}{r_j}\right)^{\gamma} E[10^{\frac{(\xi_i - \xi_j)}{10\sqrt{2}}}] \cdot P(r_i^{\gamma} 10^{\zeta_i/10} < r_k^{\gamma} 10^{\zeta_k/10}) \\ &+ E_s \left(\frac{r_k}{r_j}\right)^{\gamma} E[10^{\frac{(\xi_k - \xi_j)}{10\sqrt{2}}}] \cdot P(r_i^{\gamma} 10^{\zeta_i/10} > r_k^{\gamma} 10^{\zeta_k/10}) \end{aligned} \tag{15}$$

The mean interference power from the user in the three-way connection region can be calculated similarly.

When the user can connect with only BS$_i$ in spite of being in two-way connection region, the mean interference power to BS$_j$, $E[Is]$ becomes as follows.

$$E[Is] = E_s \left(\frac{r_i}{r_j}\right)^{\gamma} E[10^{\frac{\xi_i - \xi_j}{10\sqrt{2}}}] \tag{16}$$

From steady state probabilities obtained in Subsection 2.2.2, the mean number of MSs

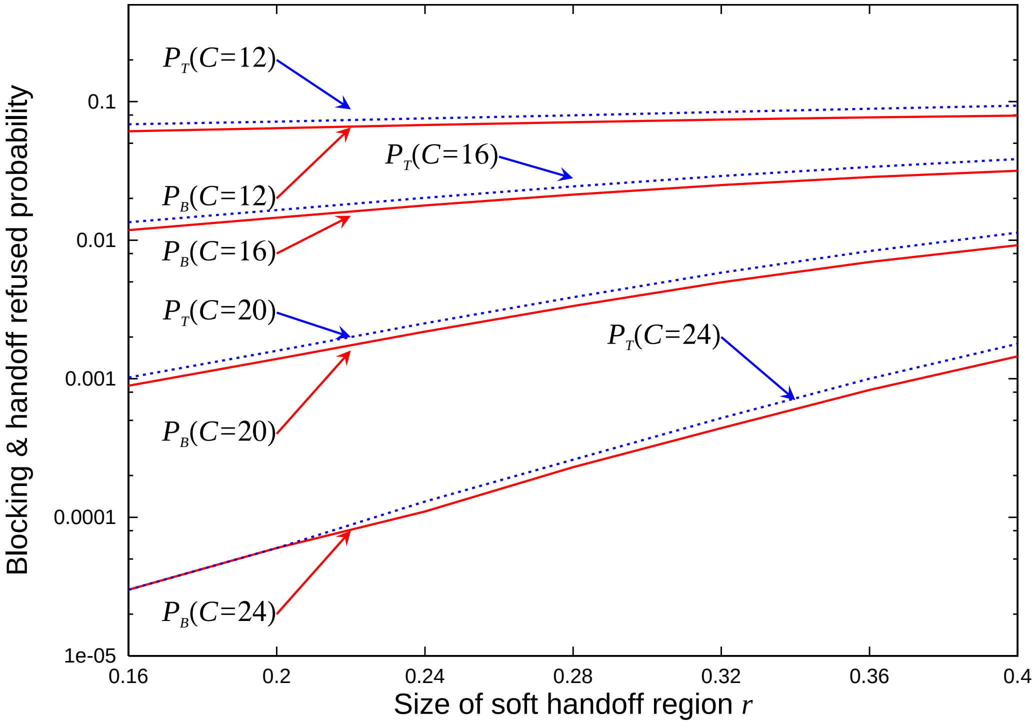

Figure 5: The effect of the number of wired channels on quality of wired channels

in the single connection region, $N_1$, is determined as follows.

$$N_1 = \sum_{n_1=0}^{C} \sum_{n_2=0}^{C-n_1} \sum_{n_3=0}^{C-n_1-n_2} n_1 p(n_1, n_2, n_3) \tag{17}$$

Similarly, the mean numbers of MSs in two-way and three-way connection regions are obtained. Alternatively, for simple calculation, interference power values from MSs in two-way and three-way connection regions are approximately calculated by assuming that MSs are in the center of each region. As to MSs in the single connection region, MSs are assumed to be in the middle of BS and boundary.

### 2.3 Numerical Examples

In this section, we show the numerical results by applying our proposed analysis method. System parameters we used are summarised in Table 1. Refer to [6] for mean call holding time, $1/\mu$, and mean residual time of MSs, $1/\mu_c$, and to [7] for voice activity factor $\nu$.

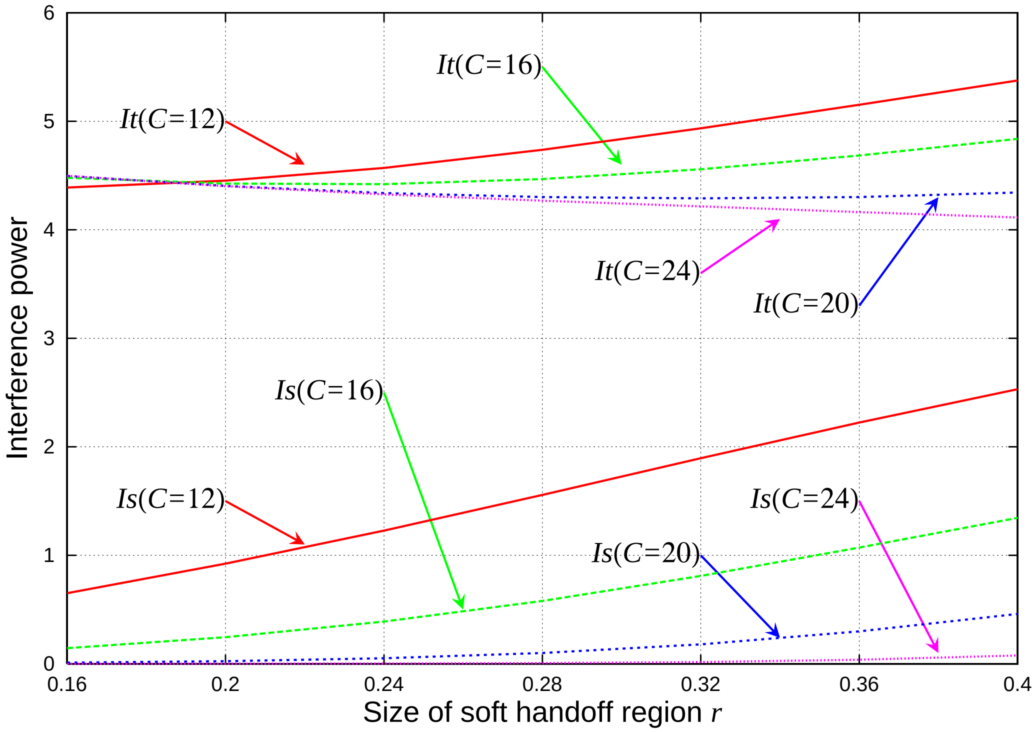

Figure 6: The effect of the number of wired channels on quality of wireless channels

### 2.3.1 The effect of the number of wired channels

We first investigate the effect of the number of wired channels on quality of wireless channels. We present the cases when the numbers of wired channels, $C$, are 12, 16, 20 and 24. Figure 5 clearly shows that less wired channels deteriorates quality of wired channels, in terms of both of blocking probability and handoff refused probability. As to quality of wireless channels, the ratio of interference power from MSs with single connection in soft

Table 1: System parameters

| | | |
|---|---|---|
| call arrival rate | $\lambda$ | 0.07 |
| mean call holding time | $1/\mu$ | 100 |
| mean | $1/\mu_c$ | 33 |
| voice activity factor | $\nu$ | 0.375 |

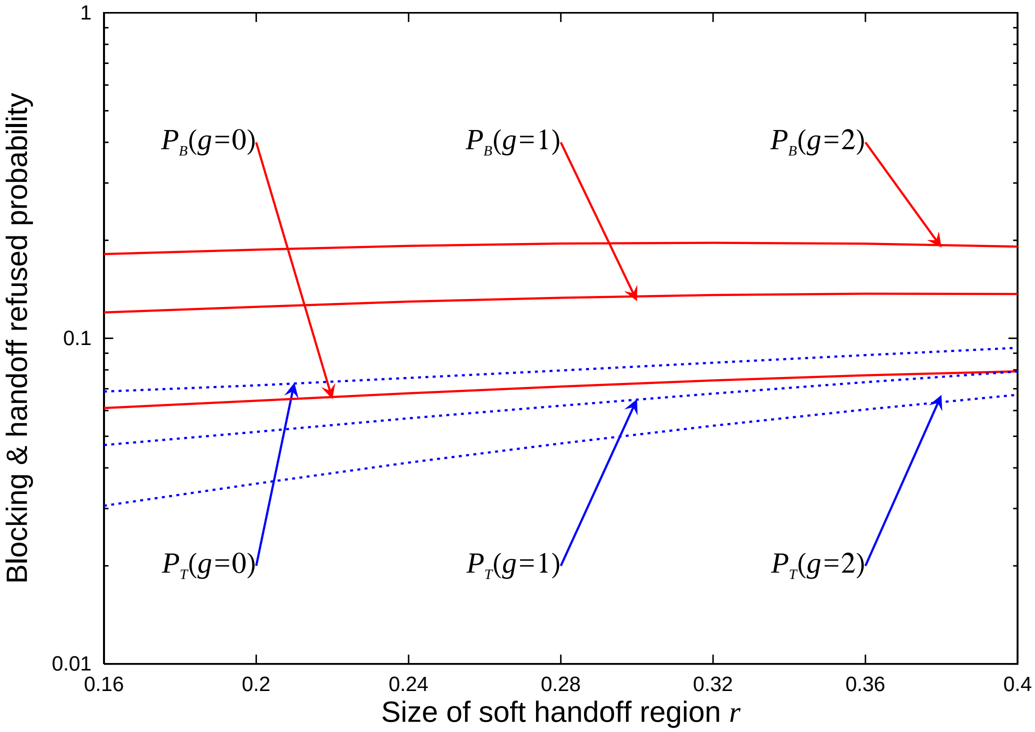

Figure 7: The effect of call admission control on quality of wired channels

handoff region $I_s$ to interference power from all MSs $I_t$ increases as the number of wired channels decreases (Figure 6). In Table 2, we show the relation between the number of wired channels and the ratio of $I_s$ to $I_t$ when the width of overlap region $r$ (Figure 1) is 0.32. As illustrated here, the smaller number of wired channels deteriorates quality

Table 2: The ratio of interference power from MSs with single connection in soft handoff region to total interference power ($r = 0.32$)

| wired channels | $I_t$ | $I_s$ | $I_s/I_t$ |
|---|---|---|---|
| 12 | 4.935 | 1.895 | 0.384 |
| 16 | 4.558 | 0.810 | 0.178 |
| 20 | 4.289 | 0.180 | 0.042 |
| 24 | 4.215 | 0.017 | 0.004 |

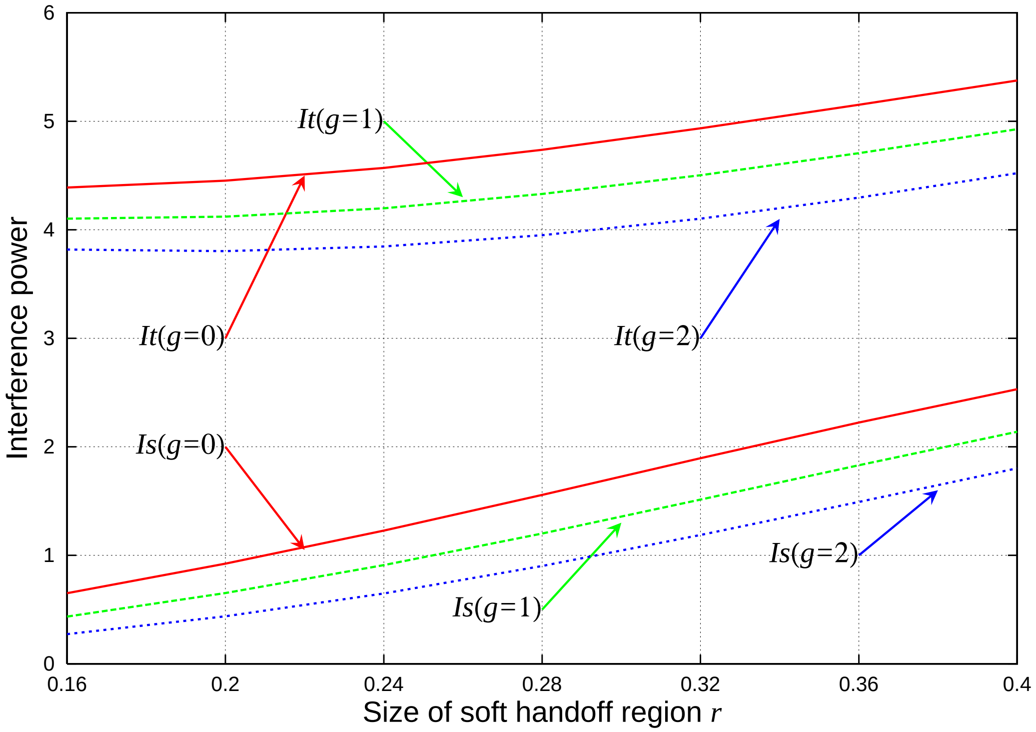

Figure 8: The effect of call admission control on quality of wireless channels

of wireless channels, because interference power from MSs with single connection in soft handoff region increases. Moreover, for $C = 20$ and $C = 24$, $I_t$ becomes lower as $r$ becomes larger. This is because MSs can enjoy soft handoff in the larger area and interference power they send becomes lower. When $C$ is small, however, some MSs cannot enjoy soft handoff because of lack of available channels and they send strong power as shown by $I_s$ in Figure 7.

### 2.3.2 The effect of a call admission control

We next present the effect of a call admission control introduced in [3] on quality of wireless channels. The control method reserves the number $g$ of wired channels for handoff calls. Handoff calls can access every channels in the BS, while calls generated in the single connection region are blocked if the number of unoccupied wired channels is $g$ or less. Then, handoff-refused probability is expected to be improved because handoff calls can obtain wired channels with higher priority over calls generated in the single connection region. The blocking probability of calls generated in the soft handoff region also improves because they can also obtain wired channels with higher priority. However, there exists one problem calls generated in the single connection region suffer higher blocking probability because wired channels in the BS are assigned to handoff calls with higher priority. We present the performance of the case when the number of wired channels reserved for handoff calls $g$ is 0 to 2 in Figure 7. It is shown that handoff-refused probability is improved as $g$ increases. Concerning the blocking probabilities, the impact of deterioration in the single connection region clearly dominates the blocking probability of the whole service area. On the other hand, the quality of wireless channels is improved by increasing $g$ (Figure 8). As shown in Subsection 2.2, quality of wireless channels is deteriorated by the lack of wired channels, which leads to more calls with single connection in the soft handoff region resulting in the cause of strong interference power.

## 3 The Effect of Soft Handoff in IMT-2000

In IMT-2000, data communications will become significant in mobile communications. Following this, downlink traffic such as web browsing increases. In downlink communication, more than one BS must send signal for MSs in soft handoff state. Therefore, the interference power of the downlink is likely to increase. For that reason, in CDMA system with soft handoff techniques, downlink quality of MSs not in soft handoff state may deteriorate when comparing with the system without soft handoff. However, an opposite observation is also possible. Downlink quality of MSs in soft handoff state may be improved by the effect of maximal ratio combining, which is a technique summing the demodulation results of groups of signals from different BSs. Moreover, in data communications, there is a retransmission mechanism. Therefore, the performance may not directly reflect the difference of quality of wireless channels.

Based on upper features of soft handoff in downlink communications, we aim at clarifying the effect of soft handoff in IMT-2000. In our simulations, we will mainly consider the influence of network load and soft handoff margin.

### 3.1 System Model

We consider the system which is divided by hexagonal cells as shown in Figure 9. The target base station in the cell is located in the center of the figure and it is represented by $\mathrm{BS}_0$. We then take account of the influence of 18 cells around $\mathrm{BS}_0$. We consider the scenario that a MS moves from $\mathrm{BS}_0$ to $\mathrm{BS}_1$, and it can be in soft handoff state by receiving signals from both $\mathrm{BS}_0$ and $\mathrm{BS}_1$. The other users are also going around the cells, but in this study, it is assumed that the user density per unit area is given by a constant, and is denoted by $\rho$. Refer to [8] for the calculation method of the number of users that each BS accommodates. We then assume that pass loss is proportional to $d^{-\mu}10^{s/10}$, where $d$ is the distance from the BS to MS, $\mu$ is the path loss slope, and $s$ means the log-normal

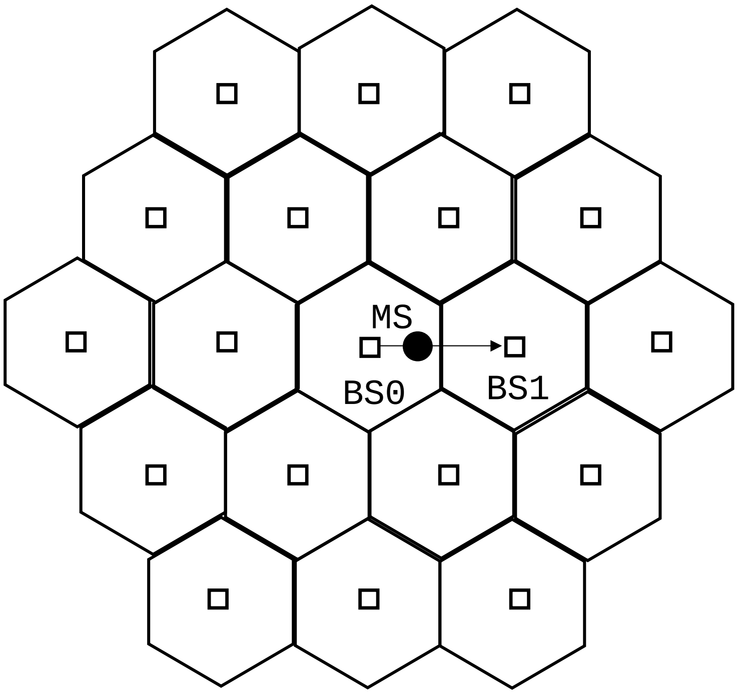

Figure 9: Cellular Layout

shadowing with zero mean and standard deviation $\sigma$. In what follows, we set $\mu = 3$ and $\sigma = 8$ following [8].

By letting $P_{r0}$ and $P_{r1}$ be the received power levels of the MS from $\mathrm{BS}_0$ and $\mathrm{BS}_1$, respectively, and $M_{SH}$ be the soft handoff margin, we can calculate the probability that the MS in the $S_2$ area in Figure 10 can connect with $\mathrm{BS}_0$ with probability $Pr(P_{r0} > P_{r1} - M_{SH})$. Then we can obtain the number of users for each BS, $N$, by the following equation:

$$N = 6 \int\int_{2S} \rho Pr\left(P_{r0} > P_{r1} - M_{SH}\right) dA \tag{18}$$

The above equation clearly demonstrates the relationship between the number of users that one BS can accommodate and the soft handoff margin. The number of users that one BS can accommodate is increased by the larger soft handoff margin. We further introduce two assumptions for the following simulation experiments. The power that each BS sends

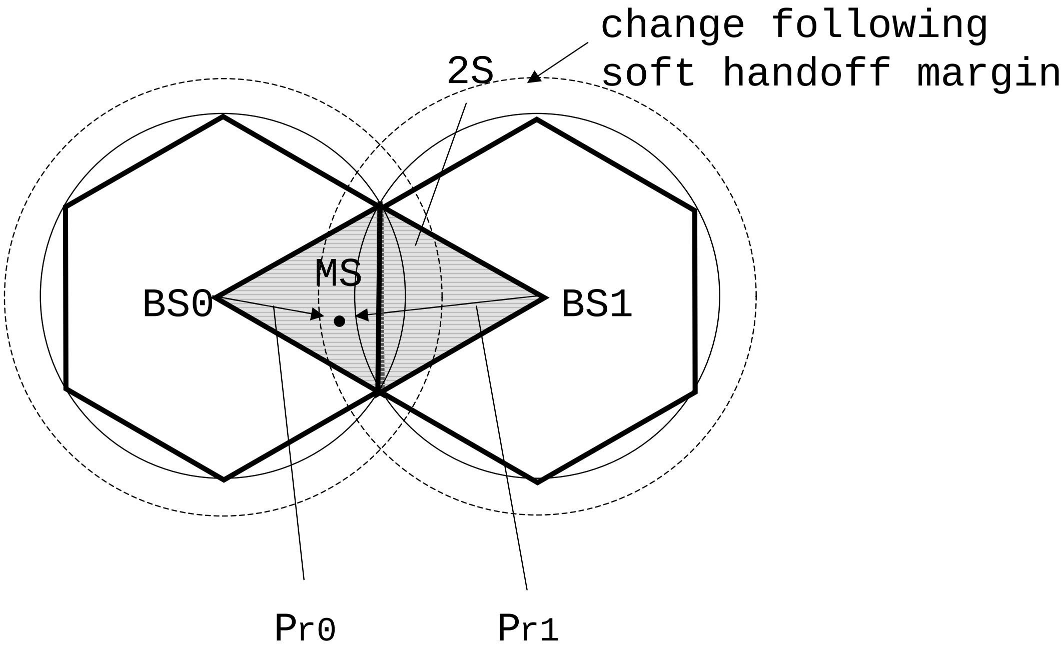

Figure 10: Soft handoff between $\mathrm{BS}_0$ and $\mathrm{BS}_1$

is identical among all BSs, and the power from each BS is divided evenly for each MS within the whole system.

With those assumptions, we now obtain energy per bit to interference power spectral density ratio, $E_b/I_0$, for each MS in the system. According to [8], $E_b/I_0$ can be calculated by giving a processing gain ($G_i$), a position of the MS in the system, the soft handoff margin ($M_{SH}$). A processing gain $G_i$ is obtained by

$$G_i = \frac{W}{r_i} \tag{19}$$

where $W$ shows the system bandwidth, and $r_i$ does a bit rate for $\mathrm{MS}_i$. Here, we show the equation for $E_b/I_0$. We then have $\gamma_i = E_b/I_0$ for MS$_i$ as [8]:

$$\gamma_i = G_i \frac{C_i}{I_{tot,i} + N_0} \tag{20}$$

where $C_i$, $I_{tot,i}$ and $N_0$ represent the received power, the interference power, and the background noise for MS$_i$, respectively.

### 3.2 Evaluation Approach

We present the comparative evaluation of soft and hard handoff techniques by the following simulation setup. The following values are used as performance measures for comparison:

- Average throughput of stationary MSs within the system
- Throughput of the MS that experiences the handoff

We will investigate the effect of following parameters on the performance:

- soft handoff margin $M_{SH}$
- user density per unit area $\rho$

Apparently, as $M_{SH}$ gets larger, the number of MS that one BS can accommodate is increased. Consequently, the transmitting power of each BS increases, and interference power for each MS also increases. On the other hand, the opportunity that the MS stays in the soft handoff state is increased by increasing value of $M_{SH}$. Because MSs in the soft handoff state receive an electric power from both of BS$_0$ and BS$_1$, they can obtain the effect of macro diversity. Moreover, if the MS is in the soft handoff state, it can achieve handoffs without disconnection. Taking those facts in mind, we want to investigate the effects of soft and hard handoffs on the system performance. We will also identify the influence of the user density. We note here that the hard handoff corresponds to the case where $M_{SH}$ is set to 0.

The communication model for each MS is illustrated in Figure 11. FH represents a Fixed–Host connected to the BS by the wired line. BS and MS are then connected by the

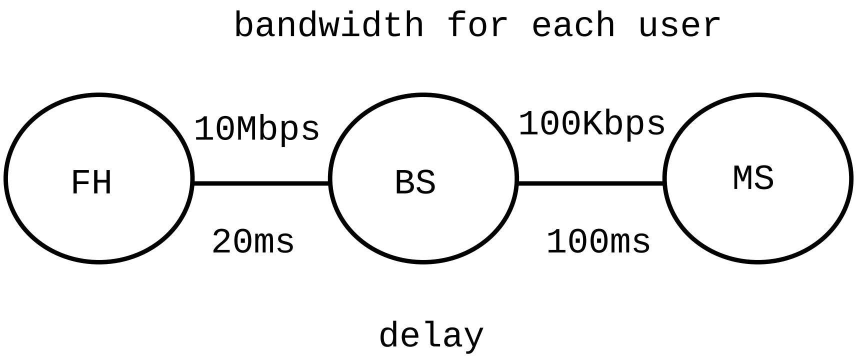

Figure 11: Network Connection Model

wireless line. In this study, we assume that every MS uses TCP for communication, and used ns-2 [9] for simulation.

In IMT-2000, QPSK is an expected modulation method. A bit error rate, $B_e$, can be derived from the signal-to-interference ratio $\gamma_i$ [10].

$$B_e = \frac{1}{2} erfc\,(\sqrt{\gamma_i}) \tag{21}$$

By assuming 20 ms frames, we use $F_n$ to represent the number of bits per frame, i.e.,

$$F_n = 20 \times 10^{-3} r_i \tag{22}$$

Then, the frame error rate, $F_e$, is simply estimated by:

$$F_e = 1 - (1 - B_e)^{F_n} \tag{23}$$

For the network layer and upper layers, we used the libraries prepared by ns-2. However, we made some assumptions on the data link layer characteristics since there is no available modules for the retransmission method in the data link layer. We model the Radio Link Protocol (RLP) used in CDMA communications as follows.

- When the frame drops at the data link layer, the arrival of packets at the network layer delays about one RTT (Round Trip Time).
- RLP limits the number of retransmission attempts. In our simulation setup, packets are lost if those cannot be sent after three retransmissions at the data link layer.

The above assumptions are implemented in ns-2 to reflect the characteristics of the data link layer protocol, RLP.

We last summarize the other system parameters used in our simulation in Table 3. See papers cited in the table for an appropriateness of chosen parameters.

### 3.3 Simulation Results

We show the simulation result in Figure 12, which shows the average throughput of stationary MSs. The average throughput of MSs that experiences handoff from $BS_0$ to $BS_1$ are presented in Figure 13.

As shown in the figures, when the network load is low, soft handoff is more effective than hard handoff for both of stationary and handoff MSs. It is because there are many MSs which can receive macro diversity effect. Furthermore, disconnection in the case of hard handoff gives an ill effect on the performance. Another reason is due to the soft handoff

Table 3: Network Environment

| | |
|---|---|
| bandwidth(BS-MS) | 100 Kbps |
| delay(BS-MS) | 100 ms [11] |
| bandwidth(FH-BS) | 10 Mbps |
| delay(FH-BS) | 20 ms [12] |
| frame length | 20 ms [13] |

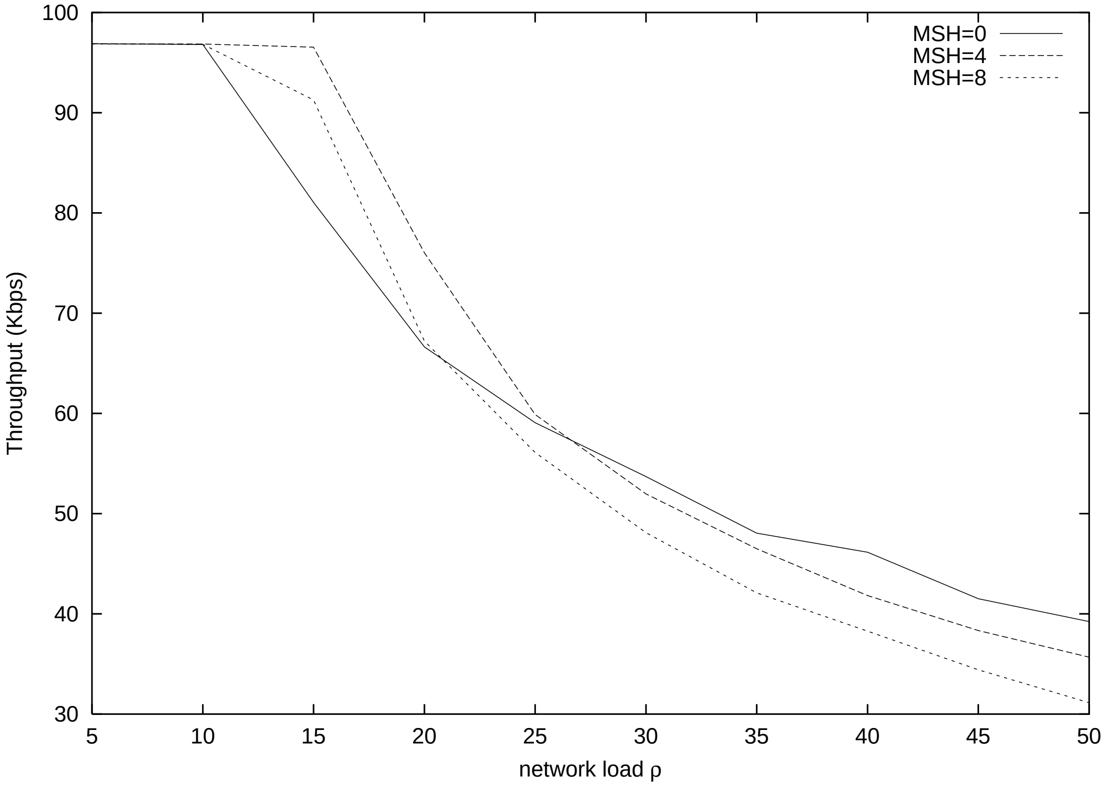

Figure 12: Average throughput of stationary MSs in the whole system

margin, $M_{SH}$, which affects the performance. In this case, soft handoff with $M_{SH} = 4$ becomes more effective when comparing to 8. When soft handoff margin becomes larger, however, MSs tend to have higher possibility being in the soft handoff state. Thus, the increase of the number of users per one BSs leads to the increase of interference power for the whole system, which results in the performance degradation in the case of the soft handoff.

When the network load is high, on the other hand, the soft handoff becomes less effective. The performance of the stationary MSs in the case of the hard handoff is even larger than that of the soft handoff. The interference power for MSs is basically large. Therefore, more increase of interference power by the soft handoff degrades the performance. Even if MSs in the boundary can receive the macro diversity effect, the performance of MSs in other regions deteriorates. Fortunately, however, the performance

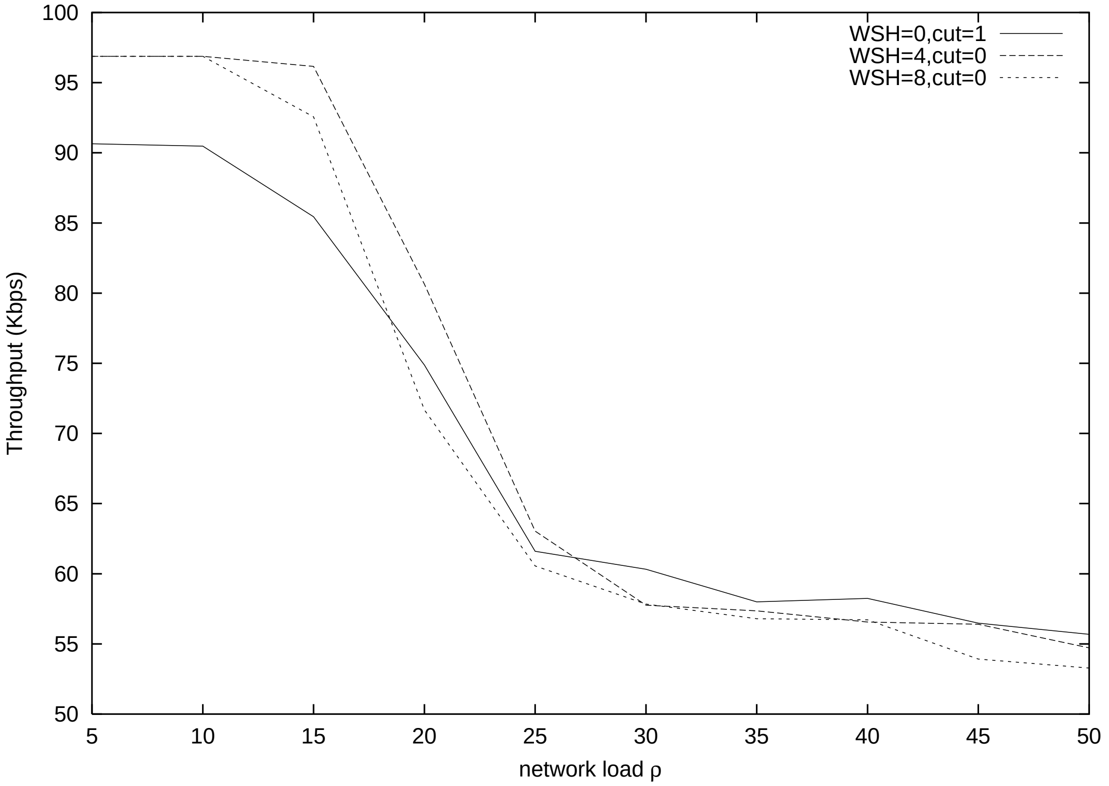

Figure 13: Average throughput of MSs which experience handoffs

result of MSs experiencing the soft handoff is still attractive. The reason is due to an existence of disconnections during the hard handoff.

As a summary, network load and/or soft handoff margin should be deliberated from a network designers' point of view for the soft handoff to be effective. For example, in the vehicular environment, introducing soft handoff would be a good choice.

# 4 Concluding Remarks

In this paper, we have proposed an analysis method for CDMA mobile cellular systems based on the consideration that integrated evaluation of qualities of both wired and wireless channels is essential for system design. We have shown that the limitation on the number of wired channels affects both qualities. Moreover, we have shown that a call admission control which considers only the quality of wired channels gives an ill effect on the quality of wireless channels.

From our results, it is apparent that adjusting system parameters by considering both qualities of both wired and wireless channels is needed for system design. This integrated evaluation is also necessary to control a system after the operation of the system starts. In this system design, system parameters are the width of soft handoff region and the number of wired channels. The number of wired channels can affects not only qualities of wired and wireless channels but also the cost of system operators. Therefore, we need to keep it small as long as both qualities satisfy users of the system.

Moreover, we have investigated the effect of soft handoff in IMT-2000 which is expected to become the major mobile network infrastructure. In IMT-2000, the downlink communication such as Web browsing is expected to increase. Soft handoff is a powerful technique especially in uplink communication by suppressing the interference power from MSs. However, in downlink communication, more than one BS must send signals for MSs in the soft handoff state.

From our results, it can be said that network configuration and traffic load affects the effect of soft handoff. When the traffic load is low, soft handoff becomes more effective than hard handoff both for stationary and handoff MSs, because many MSs can receive the macro diversity effect and seamless handoff. When the traffic load is high, on the other hand, soft handoff becomes less effective especially for stationary MSs by the increase of interference power. However, the difference between soft and hard handoff is smaller by the effect of seamless handoff. Therefore, we can say that a careful design of network following the traffic load and mobility of users should be needed.

# Acknowledgement

I would like to express my sincere appreciation to Professor Hideo Miyahara of Osaka University, who introduced me to the area of wireless networks including the subjects in this thesis.

All works of this thesis would not have been possible without the support of Professor Masayuki Murata of Osaka University. It gives me great pleasure to acknowledge his assistance. He has been constant sources of encouragement and advice through my studies and preparation of this manuscript.

I would like to express my great thankfulness to Associate Professor Masashi Sugano of Osaka Prefecture College of Health Sciences. All works of this thesis also would not have been possible without him.

I am also indebted to Assistant Professor Naoki Wakamiya, Research Associates Hiroyuki Ohsaki and Go Hasegawa of Osaka University who gave me helpful comments and feedbacks.

Finally, I thank many friends and colleagues in the Department of Infomatics and Mathematical Science of Osaka University for their support.

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