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Impact of Limited Number of Wired Channels on Soft Handoff in CDMA Cellular Systems

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SUMMARY 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. In this paper, we also clarify the effect of interference power from mobile stations that are not in the soft handoff because of lack of wired channels. 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 to wireless quality.
key words: *CDMA, three-way soft handoff, blocking probability, handoff refused probability*

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 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 is also an important result of soft handoff. On the other hand, each MS in 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 CDMA soft handoff have mainly dedicated to the wireless channel quality. Seïte [1] evaluated the tradeoff relationship between radio channel quality of uplink and downlink, and proposed a way to decide the size of the soft handoff region. Chopra et al. [2] described that introducing soft handoff causes the decrease of shadow fade margin, which leads to the increment of capacity or improvement of wireless quality. As an exception, Paik and Jin [3] have evaluated blocking probability for newly generated and handoff calls as the performance measure of CDMA systems to discuss 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 these 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 for the design of networks. Then system parameters, such as the size of soft handoff region and the number of wired channels, affect both wired and wireless qualities. For example, a larger soft handoff region makes more MSs be in soft handoff state and improves wireless quality, although it makes more MSs consume redundant wired channels in multiple BSs. This may cause deterioration of blocking probability for newly generated and handoff calls. Moreover, this limitation also deteriorates wireless quality. We show that 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 target the number of wired channels and the size of soft handoff region as system parameters, because they affect construction cost that is important 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 both wired and wireless qualities. 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 means the limitation of the number of wired channels, because it can be considered by targeting on one cell. Wireless capacity is affected by the interference power which one BS receives from MSs in whole service area. Therefore, effect from other cells should be considered. On the other hand, wired capacity can be considered by targeting only one cell. Therefore, there is some difference between them. Here, to show the necessity of integrated evaluation of both wired and wireless qualities, we firstly target the limitation of the number of wired channels.

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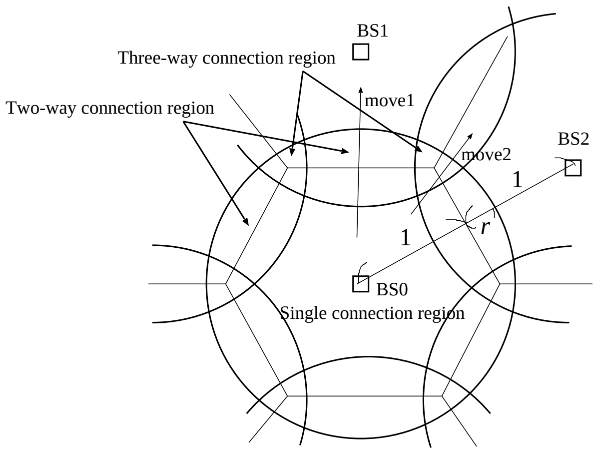

Fig. 1 Each region on the system

In this performance evaluation, we adopt an analysis method which takes three-way soft handoff into consideration. In past researches as to soft handoff, most of them assume that MSs can connect with at most two BSs simultaneously. In a practical environment, however, MSs can connect with more than two BSs as realized in IS-95 systems. Therefore, we introduce an analysis method considering that MSs can connect with three BSs simultaneously. The three-way connection influences both wired and wireless quality, because more wired channels are occupied.

Moreover, we investigate the effect of a call admission control which is introduced for improvement of handoff refused probability [3]. In the paper, the effect of such a control on only wired quality was investigated. We show that integrated evaluation of both qualities are needed when introducing such call admission controls, by indicating that they affect not only wired quality but also wireless quality.

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 considering three-way soft handoff. Then we show numerical examples by applying our analysis method in Section 4. In Section 4, we also examine the effect of a call admission control. Finally, this paper is concluded in Section 5.

2. System Model and Performance Measures

2.1 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 the 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 that are in the adjacent cells. We assume that the distance between two BSs is 2, and MSs can connect with a BS if the distance between them is $1 + r$ or less.

2.2 Evaluation of wired channels assignment

We evaluate the assignment of wired channels with blocking probability for newly generated calls and handoff refused probability. A newly generated call in each region requests channels to every BSs which it can connect with. Although a call generated in the single connection region requests a channel to only one BS, a 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 of wired channel quality.

When a MS leaves current cell, and there is no available wired channel in the cells which it moves into, it is terminated forcibly. In Figure 1, the MS which moves into single connection region (*move1*) is terminated after it loses the connection with BS0, if there is no available wired channel at BS1. A MS which moves into two-way connection region (*move2*) can connect with two BSs, BS1 and BS2, after leaving current cell. In this case, it is terminated 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 wired channel quality.

Note that MSs can be in single connection state even if they are in soft handoff region, when 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 boundary of each region.

2.3 Evaluation of wireless channel quality

We focus on the uplink to evaluate wireless channel quality. This is because the soft handoff mainly affects wireless channel quality of uplink [4], [5]. As a performance measure of wireless channel quality, we adopt interference power that each BS receives. When considering a MS connecting with a BS, the power that the BS receives from other MSs becomes interference power for that MS. In CDMA systems, wireless quality of the MS deteriorates as the interference power becomes stronger, because wireless quality 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 always receive signals from accommodating MSs at same power. Therefore, we can evaluate wireless quality of a MS by interference power from other MSs.

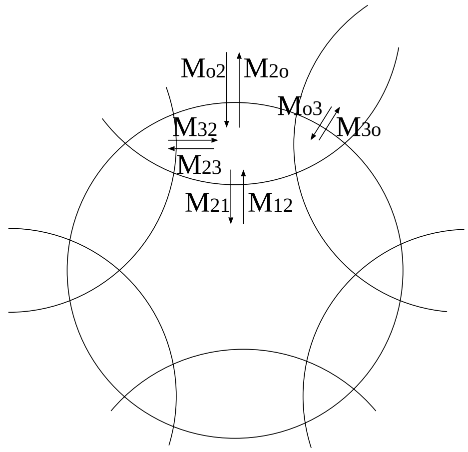

Fig. 2 Transition probability for MSs between each regions

3. The Analysis Method Considering Three-way Soft Handoff

Here, we show our analysis method to obtain performance measures which we explain in previous section. Firstly, we consider wired channels and derive blocking probability and handoff refused probability. Also, we obtain the number of MSs in each area at the steady state. By using it, we will derive 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 single connection region is denoted as n_1, and the number of calls in two-way and three-way connection region is n_2 and n_3, respectively. The state of occupied wired channels is 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 λ. Call arrival rates in each region, λ_1, λ_2, λ_3, can be obtained according to area of each region, A_1, A_2 and A_3 (single connection, two-way connection and three-way connection regions).

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

We also assume that call holding time and residual time of MSs in each region follow the exponential distribution. We denote mean call holding time as $1/\mu$, and show an analysis method by illustrating the case of single connection region in the following.

3.1 Mean residual time of MSs

We first show a determination method of a mean residual time of MSs in each region. We assume that MSs move at a fixed speed and never change its direction for simplicity. Mean residual time includes both cases of newly generated calls and handoff calls. Therefore it is desired to calculate a weighted average by considering the number of both calls. However, we substitute a mean residual time of newly generated calls for easy calculation. We assume that calls are generated uniformly in the cell and MSs travel every direction with same probability. Firstly, we 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 providing mean residual time in the unit cell $1/\mu_c$. For two-way and three-way connection regions, we can obtain mean residual times $1/\mu_2$ and $1/\mu_3$ similarly.

Concerning MSs in the two-way connection region, they can move into both single and three-way connection regions. When calculating a distance of each coordinate to each direction, we count the number of MSs to each region, N_{21} and N_{23}. We also calculate the mean distance for each region, d_{21} and 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.

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

The probability that MSs move into three-way connection region is expressed as $1 - R_1$. The probability that MSs move away from two-way connection region is denoted as μ_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 (μ_{21} and μ_{23}, respectively) is expressed as follows.

$$\mu_{21} = R_1\mu_2, \quad \mu_{23} = (1 - R_1)\mu_2 \tag{4}$$

3.2 Blocking probability and handoff refused probability

We obtain the number of MSs in each region in the steady state by considering state transition probabilities, where the state of the number of occupied channels in each region is expressed as (n_1, n_2, n_3). State transitions occur by 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.

$$M_{12} = n_1\mu_1, \quad M_{21} = (1/2)n_2\mu_{21}$$
$$M_{23} = n_2\mu_{23}, \quad M_{32} = (2/3)n_3\mu_3$$

$$M_{2o} = (1/2)n_2\mu_{21}, \quad M_{o2} = A_{n_1}\mu_1$$
$$M_{3o} = (1/3)n_3\mu_3, \quad M_{o3} = (1/2)A_{n_2}\mu_{21}$$

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

$$A_{n_1} = \sum_{n_1=0}^{C}\sum_{n_2=0}^{C-n_1}\sum_{n_3=0}^{C-n_1-n_2} n_1 p(n_1,n_2,n_3) \tag{5}$$

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

$$\begin{aligned}
&\{\lambda_1{+}\lambda_2{+}\lambda_3{+}(n_1{+}n_2{+}n_3)\mu{+}A_{n_1}\mu_1 \\
&+(1/2)A_{n_2}\mu_{23}{+}(1/2)n_2\mu_{21}{+}(1/3)n_3\mu_3{+}n_1\mu_1 \\
&+(1/2)n_2\mu_{21}{+}n_2\mu_{23}{+}(2/3)n_3\mu_3\}p(n_1,n_2,n_3) \\
&=\lambda_1 p(n_1{-}1,n_2,n_3){+}(\lambda_2{+}A_{n_1}\mu_1)p(n_1,n_2{-}1,n_3) \\
&+(\lambda_3{+}A_{n_2}\mu_{23})p(n_1,n_2,n_3{-}1) \\
&+(n_1{+}1)\mu p(n1{+}1,n_2,n_3)1_{\{n_1+n_2+n_3<C\}} \\
&+(n_2{+}1)(\mu{+}(1/2)\mu_{21})p(n_1,n_2{+}1,n_3)1_{\{n_1+n_2+n_3<C\}} \\
&+(n_3{+}1)(\mu{+}(1/3)\mu_3)p(n_1,n_2,n_3{+}1)1_{\{n_1+n_2+n_3<C\}} \\
&+(n_1{+}1)\mu_1 p(n_1{+}1,n_2{-}1,n_3) \\
&+(1/2)(n_2{+}1)\mu_{21}p(n_1{-}1,n_2{+}1,n_3) \\
&+(n_2{+}1)\mu_{23}p(n_1,n_2{+}1,n_3{-}1) \\
&+(2/3)(n_3{+}1)\mu_3 p(n_1,n_2{-}1,n_3{+}1)
\end{aligned} \tag{6}$$

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

$$\sum_{n_1=0}^{C}\sum_{n_2=0}^{C-n_1}\sum_{n_3=0}^{C-n_1-n_2} p(n_1,n_2,n_3) = 1 \tag{7}$$

Note that, as shown in equation 5, the arrival rate of handoff calls depends on steady state probabilities. Therefore we repeat the above calculations. The probability that every available channels are occupied in the target cell p_f is denoted as the probability $n_1{+}n_2{+}n_3 = C$, and expressed as follows.

$$p_f = \sum_{(n_1,n_2,n_3);n_1+n_2+n_3=C} p(n_1,n_2,n_3) \tag{8}$$

The blocking probability of calls generated in each single, two-way, three-way connection regions becomes p_f, p_f^2 and p_f^3, respectively, according to the number of BSs which they can connect with. We can calculate blocking probability in the whole service area, P_B, from weighted average by considering call arrival rate in each region. By considering that the service area is divided by hexagonal cells (See Figure 1), P_B becomes

$$P_B = \frac{\lambda_1 p_f + \frac{1}{2}\lambda_2 p_f^2 + \frac{1}{3}\lambda_3 p_f^3}{\lambda} \tag{9}$$

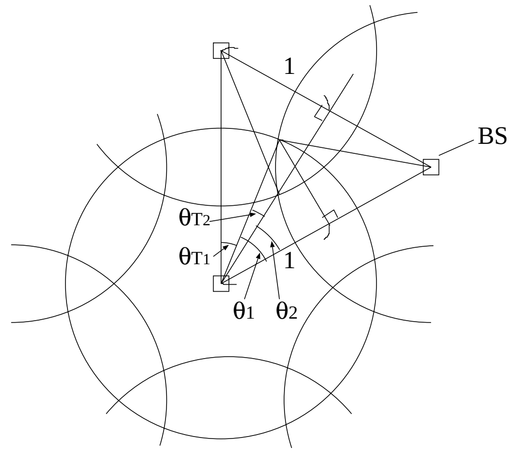

Fig. 3 Transition of handoff calls

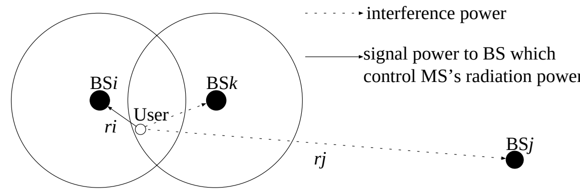

Fig. 4 Interference power from the user in soft handoff state

In what follows, we explain the calculation method of the handoff refused probability. We assume that the MS moves away the current cell equally on the every border. Accordingly, the ratio of the number of MSs which move into single connection region to the number of 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.

$$\theta_1 = \cos^{-1}\frac{1}{1+r}, \quad \theta_2 = \frac{\pi}{6}$$
$$\frac{\theta_{T_1}}{\theta_{T_2}} = \frac{\frac{\pi}{3}-\theta_1}{\theta_1-\theta_2} \tag{10}$$

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

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

3.3 Calculation of interference power

We express the wireless quality by interference power. Interference power from each user can be calculated by referring to [5]. In the paper, the power that each MS radiates (E_{trans} in our paper) is assumed to be ideally controlled and be received at 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 distance attenuation and shadowing effect. That is, the required power from BS_i is smaller for the user than that from 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. 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

$$\zeta_i = \frac{1}{\sqrt{2}}\xi + \frac{1}{\sqrt{2}}\xi_i \qquad (12)$$

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

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

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

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

We introduce another assumption to calculate interference power which one 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 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.

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

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 from the user which BS_j receives, $E[Is]$ becomes as follows.

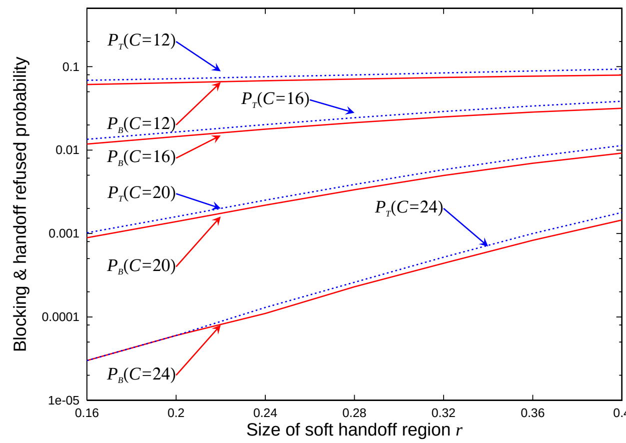

Fig. 5 The effect of the number of wired channels on wired qualities

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

From steady state probabilities obtained in Subsection3.2, the mean number of MSs in single connection region, N_1, is determined as follows.

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

Similarly, the numbers of MSs in two-way and three-way connection regions are obtained. Alternatively, for simple calculations, 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.

4. Numerical Examples

In this section, we show the numerical results by applying our proposed analysis method. System parameters we used are shown 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 ν.

4.1 The effect of the number of wired channels

Here, we show the effect of the number of wired chan-

Table 1 System parameters

call arrival rate	λ	0.07
mean call holding time	$1/\mu$	100
mean	$1/\mu_c$	33
voice activity factor	ν	0.375

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

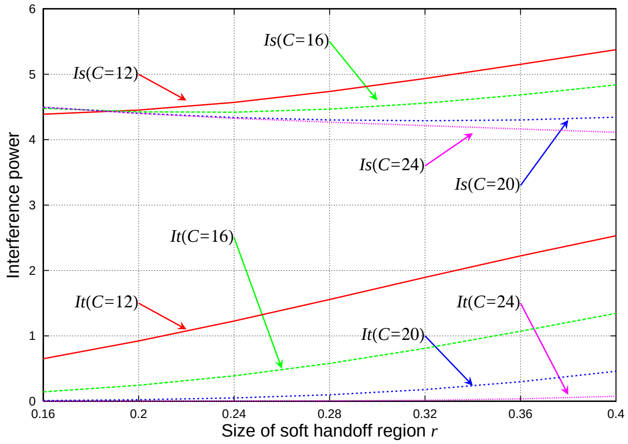

Fig. 6 The effect of the number of wired channels on wireless quality

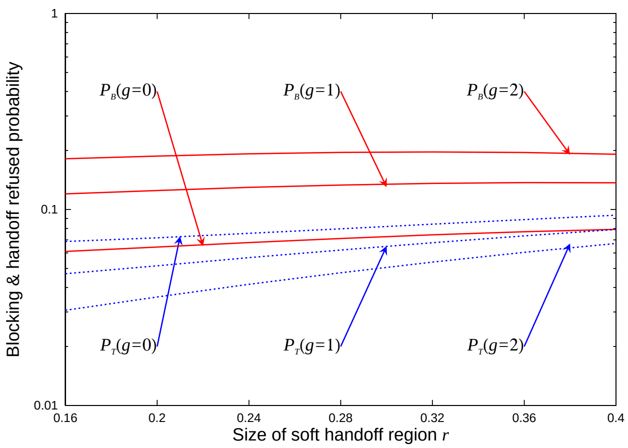

Fig. 7 The effect of a call admission control on wired quality

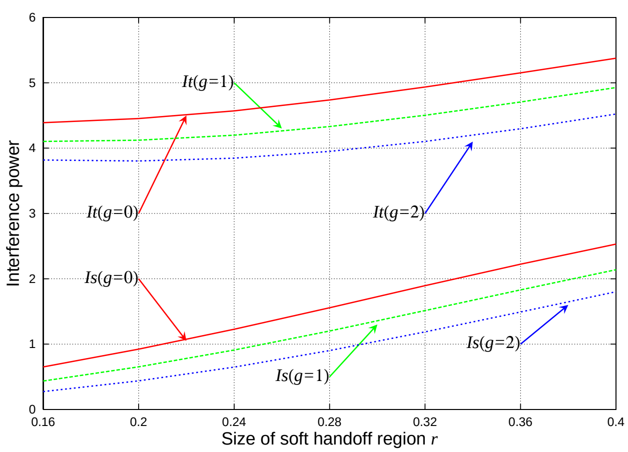

Fig. 8 The effect of call admission control on wireless quality

nels on wireless quality. 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 wired quality, both blocking probability and handoff refused probability. As to wireless quality, the ratio of interference power from MSs with single connection in soft 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 wireless quality 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 at 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.

4.2 The effect of a call admission control

Here, we show the effect of a call admission control introduced in [3] on wireless quality. 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 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 single connection region. The blocking probability of calls generated in soft handoff region also improves because they can also obtain wired channels with higher priority. However, there exists one problem that calls generated in the single connection region suffer higher blocking probability because wired channels in a 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 improves as g increases. Concerning blocking probability, the impact of deterioration in the single connection region dominates blocking probability of the whole service area. On the other hand, the wireless quality is improved by the increase of g (Figure 8). As shown in Section 3, wireless quality is deteriorated by the lack of wired channels, which leads to more calls with single connection in soft handoff region resulting in the cause of strong interference power.

5. Conclusion and future work

In this paper, we have proposed an analysis method for CDMA mobile cellular systems based on the consideration that integrated evaluation of both wired and wireless qualities 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 wired quality gives an ill effect on the wireless quality.

From our results, it is apparent that adjusting system parameters by considering both wired and wireless qualities 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 wired and wireless qualities but also the cost of system operators. Therefore, we need to keep it small as long as both wired and wireless qualities satisfy users of the system.

As the future work, we should evaluate both qualities by taking wireless capacity into account. Then we want to make it clear how we should design systems to reduce the construction cost as long as qualities requested by users are satisfied.

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