PAPER

Distribution of *ISR* and Its Optimization in Performance Evaluation of Forward Link in Cellular Mobile Radio Systems*

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SUMMARY In CDMA systems, power control strategy is the most important issue since the capacity of the system is only interference-limited. For a better understanding of the effects of Forward Link Power Control Strategy *(FLPCS)* on the outage probability in fading environments, this paper has presented a theoretical analysis of forward link in a CDMA cellular system by introducing the τ-th power of distance driven control strategy. Based on the power control, the capacity and outage probability of the system are estimated and discussed. In particular, we consider the impact of fading environments and investigate the "hole" phenomenon. Based on our numerical results, the "hole" points are at the upper bounds of where it is possible to ensure minimization of the maximum value of total Interference-to-Signal Ratio (ISR) [4]. At those upper bound points, at least, the power control strategy leads to approximately threefold the capacity compared to the case without power control strategy. It can be concluded that the forward link without power control strategy is a very heavy restriction for the capacity of the CDMA system, especially in environments of significant fading.

key words: *forward link (base station-to-mobile), reverse link (mobile-to-base station),* τ*-th power of distance driven,* ISR *driven, soft handoff*

1. Introduction

Cellular mobile systems were designed to increase the traffic capacity in the service area. CDMA technique has attracted much attention for its high capacity in the system and high-spectrum efficiency. Power control strategy is an important problem in cellular wireless system, not only in Frequency-Division Multiple-Access (FDMA) and Time-Division Multiple-Access (TDMA) cellular systems. In these systems, power control plays an important role in reducing the co-channel interference due to channel reuse in cellular system. In CDMA systems, power control strategy is the most important problem since the capacity of the system is only interference-limited which has been identified by Lee [1], R.R. Gejji [2], and R. Prasad [3].

In CDMA, since all users in the cellular system share the same frequency bandwidth, estimation of capacity and outage probability requires that a large number of cells be considered. Power control strategy must be implemented to ensure the threshold value for the energy per bit-to-noise power spectral density ratio, E_b/N_0 and maximum capacity. Usually, there are two approaches to estimating the forward link in cellular mobile systems, as follows:

(1) Distance Driven [1], [2]: It is the power control strategy that with the knowledge about the position of mobile users, base station changes the transmission power at a higher power level to the users located at the cell boundary and with lower power level to the users located near to the base station that is to ensure required value of received power level at each user in the cell. In Refs. [1] and [2], using simple analytical models for the system, they did not consider the impact of fading environments, which play an important role and generate great effects on the mobile systems. Dr. W. Lee concluded the capacity will be increased near three times when adopt the power control strategy in Ref. [1].

(2) ISR Driven [3], [4]: Here, ISR is defined as the Interference-to-Signal Ratio [4]. It has been used in some papers [3], [4] in order to conveniently calculate the intercellular interference (other-cell user interference) and outage probability according to some significant features of CDMA cellular system, such as soft-handoff [4], [5]. It can be directly converted into general Signal-to-Interference Ratio (SIR) by $SIR = 1/ISR$ during the investigation. The method implies that the ISR of each user is minimized depending on the individual need of each user located in the cell in a more general setting and leads to somewhat complicated algorithms. Unfortunately, none of those algorithms are easy to estimate ISR or BER perfectly in complex long-term and short-term fading environments. Because ISR driven can not been denoted by the theoretical equations, then Refs. [3] and [4] adopted Monte Carlo simulation method and obtained statistical average results. In our theoretical model, we dismiss the ISR driven and adopt the distance driven in our investiga-

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tion.

Because ISR driven is too complex to allow realistic models to be evaluated analytically. In this work, we adopt distance driven to express the relationships that compose the system model and power control strategy. It is suitable for us to consider the mathematical methods to obtain exact information on questions of interest, which is called an analytic solution. That is why the distance driven was often used in the investigations [1], [2]. Therefore we have been deeply impressed by Dr. W. Lee's views on the distance driven, applied ourself to rigorous theoretical inquiries.

In spite of the vast literature on forward link of CDMA cellular systems, some important issues are not fully assessed as yet, especially, the theoretical approach under considering fading environments and optimal issue of the power control strategy. Because of distance driven, the upper bound points of ISR change and move from the boundary to the intermediate region of the cell. The upper bound points are defined as "hole" points [2]. It is a optimal issue to keep ISR of the upper bound point to the minimum. The model developed here will be used to investigate these issues on the forward link, which has not been fully investigated as yet. We carry out a complete system analysis of the forward link, considering power control strategy and fading environments. The objectives are threefold. Firstly we analyze CDMA cellular architectures and effects of surrounding cells. Secondly the effects of the τ-th power of distance driven control strategy on the system are evaluated and quantified. Finally, the effects of different propagation statistics of long-term fading [5], [6] are estimated. Short-term fading is assumed as negligible. The analytical results are validated against previous methods in Refs. [2] and [3].

This paper is organized and presented as follows. Section 2 describes a discussion of the system model for forward link in the system and the τ-th power of distance driven control strategy. In Sect. 3, the multi-cell multi-users interference is analyzed for the CDMA cellular system with soft handoff, distance driven control strategy. The capacity, outage probability and the "hole" issue are also described. The effects of the processing gain, G, voice activity monitoring, α and the power control parameter, τ on capacity and outage probability are quantified and discussed in Sect. 4, in which we also address the numerical results and discussions. Section 5 offers the conclusions.

2. System Model and FLPCS Strategy

This section outlines the forward link model of a CDMA cellular system employing the τ-th power of distance driven. The system performance is given a function of power control strategy, fading parameters and so on. Here, we model the cellular system shown in Fig. 1 as follows:

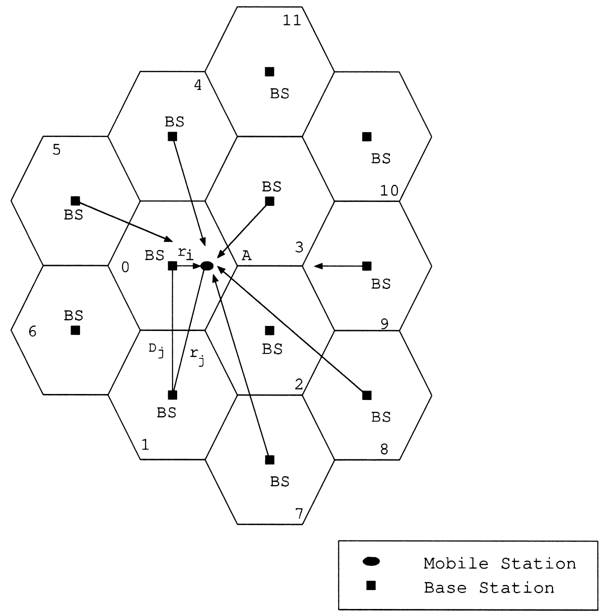

Fig. 1 Cellular system structure.

1) The investigation was motivated by IS-95 [7], [8] specification, in which the information bit rate R_b and the spread bandwidth W_{ss} are given by 9.6 kbps and 1.2288 MHz, which is the cellular CDMA mobile system standardized in United State.

2) The same spread bandwidth, W_{ss} is reused in every cell. The wanted signal is ideally separated from the other users by means of a pseudo-noise (PN) codes, which are uncorrelated, absolutely.

3) Assuming a uniform density of users located in every cell. We consider the standard uniform hexagonal layout as shown in Fig. 1 with a base station (BS) at the center of every cell. The BS and user antennas are assumed to be omni-directional. Cell selection is governed by minimum distance between the user and the home cell BS.

4) The forward link and reverse link use disjoint frequency bandwidths and can thus be analyzed independently. Both links are considered herein.

2.1 Interference Geometry

The geometry of the interference model is shown in Figs. 2 and 3. The interference generated by the users in the reference cell (0-th cell) is defined as intracellular interference. The interference from the users located in surrounding cells is defined as intercellular interference. The reference mobile user is communicating with its BS (0-th BS) in the presence of intracellular interference and intercellular interference from other BSs (1-st BS to 11-th BS) in our model [9], [10].

For the reference mobile user located at a distance r_i in the reference cell (0-th cell), the distance r_j from the reference mobile user to the j-th interfering BS is

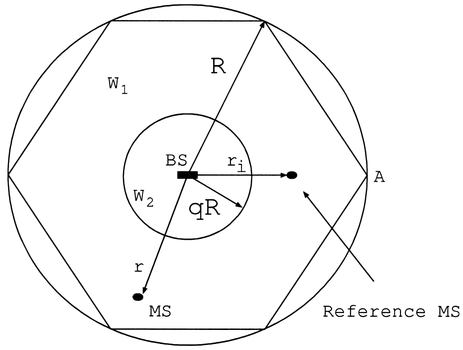

Fig. 2 Intracellular interference architecture of the 0-th cell ($Z = W_1 + W_2$, based on the power control model, i.e., Eq. (3)).

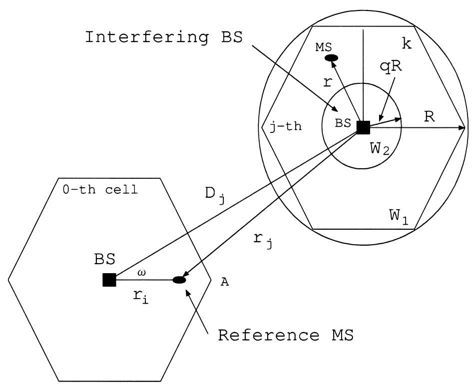

Fig. 3 Intercellular interference architecture.

calculated as

$$r_j = \sqrt{D_j^2 + r_i^2 - 2D_j r_i \cos\omega} \quad (1)$$

In Eq. (1), D_j is the distance between the 0-th BS and the j-th surrounding BS. ω is defined as the angle between the D_j and r_i as shown in Fig. 3.

2.2 Propagation Model and Power Control Strategy

For general propagation loss of electronic signal, three factors are associated with the propagation loss, i.e., distance path loss, long-term fading and short-term fading. According to the significance of different kinds of fading in wireless channel, the most significant fading is the long-term fading. In Refs. [3], [4] and [5], the effects of long-term fading were considered in their investigations. The effects of short-term fading are negligible, because the short-term fading is caused by multi-path propagation. The effects can be mitigated and controlled easily by means of proper techniques such as Rake receiver, diversity reception by space-time coding and coding with interleave, etc. Then in this paper, only long-term fading is considered. Furthermore, in CDMA systems, the real advantage is the nature of the human conversation feature, i.e., the voice activity monitoring can been used for reducing mutual interference. The received signal, P_r because of the propagation loss between BS and user can be expressed as follows [10], [11]

$$P_r = \begin{cases} \left(\dfrac{\lambda}{4\pi}\right)^2 \dfrac{\psi}{r^2} P_t 10^{\frac{\zeta}{10}} & r \leqq d \\ (h_{bs}h_m)^2 \dfrac{\psi}{r^4} P_t 10^{\frac{\zeta}{10}} & r > d \end{cases} \quad (2)$$

where,

$$d \equiv \frac{4\pi h_{bs} h_m}{\lambda}$$

In Eq. (2), P_t is the transmission power from BS, r is the distance between the user and the BS, λ is the wavelength (i.e., carrier frequency), h_{bs} is the BS antenna height, and h_m is the user antenna height. ψ denotes the voice activity variable, which is equal to one with probability of α and to zero with probability of 1-α, where α is defined as voice activity monitoring factor [3]. ζ is a Gaussian random variable because of long-term fading, with standard deviation,σ and zero mean [4]. The break point, d is determined by h_{bs}, h_m and λ. Note that the BS antenna heights differ with corresponding difference in user antenna heights, as well as in d.

For the power control strategy, we do not focus on how to complete the power control strategy, such as fast power control methods [14], [15] and a stochastic power control method [8]. We only focused the research on the system performance investigation after the power control [1], [2] has been successfully performed. Here, the forward link power control strategy is assumed to be similar to Ref. [1] termed as the τ-th power of distance driven, i.e., the transmission power for each user is different according to the distance between the BS and the user. The transmission power $P(r)$ for a user located at a distance r from the BS as shown in Fig. 2 is obtained by

$$P(r) = \begin{cases} P_{req} \ \ q^{\tau} & 0 \leqq r \leqq qR \\ P_{req} \ \ \left(\frac{r}{R}\right)^{\tau} & qR < r \leqq R \end{cases} \quad (3)$$

where in Eq. (3), R is a radius of the cell. P_{req} is the transmission power required to reach the users located at the boundary between cells. q is the power control parameter ($0 \leqq q \leqq 1$). As shown in Fig. 2, based on Eq. (3), W_1 and W_2 are defined as the outside area of the cell $qR < r \leqq R$ and inner area of the cell $0 \leqq r \leqq qR$, respectively, that means the region of one cell is composed of W_1 and W_2.

Based on the power control strategy [1], [2] described in Eq. (3), it is possible to minimize the total power transmitted by each BS by such a controlled transmission with higher power to the users located at the cell boundary and with lower power to the users close to the BS in order to solve the near-far problem [3], [4]. To avoid excessive decrease in receiving power, so that each user located at distance r shorter than

qR is assumed to receive a minimum amount of transmission power from BS for the user benefice. As is well known, the most important goal of forward link power control strategy is to finish the uniform service; the same ISR [1], [2] of each user as equal as possible wherever the user dwells in the cell. To complete this goal, the power control parameter q should be selected carefully with a constant value of τ during the optimization.

Mobile users are assumed here to be uniformly distributed in an equivalent disc of radius R shown in Fig. 2. The density function of mobile users in a cell is

$$f(N, R) = \frac{N}{\pi R^2} \tag{4}$$

where N is the total number of active users in one cell. After some mathematical manipulation, we obtained the total transmission power P_t required in one cell with the τ-th power of distance driven control as

$$\begin{aligned} P_t &= 2\pi P_{req} f(N, R) \left\{ \int_0^{qR} q^\tau r dr + \int_{qR}^{R} \Big(\frac{r}{R}\Big)^\tau r dr \right\} \\ &= N P_{req} \left\{ q^{\tau+2} + \frac{2}{\tau+2}(1 - q^{\tau+2}) \right\} \end{aligned} \tag{5}$$

If we do not adopt the power control strategy, the full power P_{req} is necessary for each user in a cell, then the total transmission power $P_t = NP_{req}$. Comparing the total transmission power with Eq. (5), we obtained the reduction function η as

$$\eta = q^{\tau+2} + \frac{2}{\tau+2}(1 - q^{\tau+2}) \tag{6}$$

where we select different τ to obtain the reduction of transmission power. If we select τ=0, we obtain the situation without power control strategy, i.e., η=1. The reduction function η versus q is plotted in Fig. 4 with different τ. According to the curves, q decreases, the reduction function η becomes flat. If we set q=0, we obtain the basic situation in Ref. [1], i.e., $\eta = \frac{2}{(\tau+2)}$.

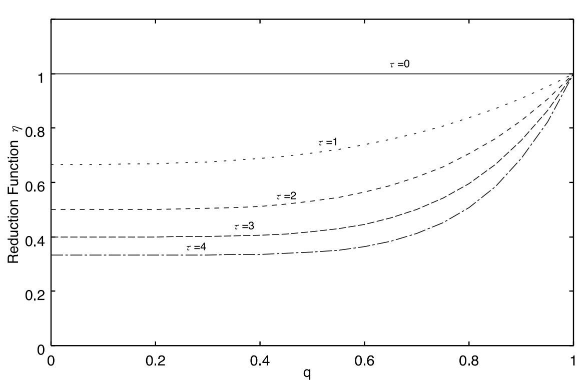

Fig. 4 Reduction function η versus q with different τ.

3. Theoretical Analysis

3.1 Intracellular and Intercellular Interference-to-Signal Ratio

In the CDMA systems, energy transmitted by BSs for all users occupies the same spread bandwidth at the same time. Hence, interfering sources cover all the BSs for forward link. There are no Guard-bands among users. The geometry of the interference model is shown in Figs. 2 and 3. We will consider the i-th reference user located at a distance r_i on the line from the BS to the point A in Fig. 2. We will consider the intracellular interference and the intercellular interference generated by the surrounding eleven cells as shown in Fig. 1.

In the service area, if the BS transmits power $P(r_i)$ for the i-th reference user, substituting Eq. (3) into Eq. (2), the wanted signal received by the reference user located at the distance r_i is

$$S = \begin{cases} k_1 \dfrac{1}{r_i^2} P_{req} q^\tau 10^{\frac{\zeta_i}{10}} & 0 < r_i \leqq d \\ k_2 \dfrac{1}{r_i^4} P_{req} q^\tau 10^{\frac{\zeta_i}{10}} & d < r_i \leqq qR \\ k_2 \dfrac{1}{r_i^4} P_{req} \Big(\dfrac{r_i}{R}\Big)^\tau 10^{\frac{\zeta_i}{10}} & qR < r_i \leqq R \end{cases} \tag{7}$$

where,

$$k_1 = \left(\frac{\lambda}{4\pi}\right)^2,$$

and

$$k_2 = (h_{bs} h_m)^2.$$

Based on the wanted signal in Eq. (7), the cell is composed of three areas according to the location of the reference user. In the following section, we induce the formulations about the situation of the reference user located in outer area, $qR < r_i \leqq R$ in the 0-th cell. The formulations about the reference user located in the area, $d < r_i \leqq qR$ and the area, $0 < r_i \leqq d$ in the cell can be derived by the same method depicted in this section. In all formulations, if we set $\tau = 0$, the situation of the system becomes a cellular system without power control strategy used in the forward link investigation as Ref. [5].

The intracellular interference is the interference generated by the users which are power controlled by the reference BS (0-th BS) shown in Fig. 2. As the reference user located in its cell receives a composite signal from its cell base-station composed of the wanted signal and N interfering signals for the users uniformly distributed in the cell. The mean of the total intracellular interference-to-signal ratio $(\frac{I_{int}}{S})_t$ from other channel transmission power in its own cell when the reference user located at $qR < r_i \leqq R$ area of is [2], [3]

$$E\left[\left(\frac{I_{int}}{S}\right)_t\right] = 2\alpha\frac{N}{R^2}\left\{\int_{qR}^{R}\left(\frac{r}{r_i}\right)^{\tau} rdr + \int_0^{qR} q^{\tau}\left(\frac{R}{r_i}\right)^{\tau} rdr\right\} = \eta N\alpha\left(\frac{R}{r_i}\right)^{\tau} \quad (8)$$

Using the same method, we can obtain the mean of the total intracellular interference-to-signal ratio $\left(\frac{I_{int}}{S}\right)_t$ from other channel transmission power in its own cell when the reference user located at each area of the 0-th cell summarized as

$$E\left[\left(\frac{I_{int}}{S}\right)_t\right] = \begin{cases} \eta N\alpha\frac{1}{q^{\tau}} & 0 < r_i \leqq qR \\ \eta N\alpha\left(\frac{R}{r_i}\right)^{\tau} & qR < r_i \leqq R \end{cases} \quad (9)$$

The interference from the users which are controlled by surrounding base stations is defined as intercellular interference. The intercellular interference-to-signal ratio $\left(\frac{I_{ext}}{S}\right)_{W_1}$ for the reference user located at the area, $qR < r_i \leqq R$ of the 0-th cell, from one external user located in the outer area, W_1 in surrounding j-th cell modelled as shown in Fig. 3 is [12], [13]

$$\left(\frac{I_{ext}}{S}\right)_{W_1} = \psi k_3 r^{\tau} 10^{\frac{\zeta_j-\zeta_i}{10}} \quad (10)$$

where,

$$k_3 = \left(\frac{r_i}{r_j}\right)^4\left(\frac{1}{r_i}\right)^{\tau}.$$

Using the same method, the intercellular interference-to-signal ratio $\left(\frac{I_{ext}}{S}\right)_{W_2}$ for the reference user located at the same area from one external user located in the inner area, W_2 in surrounding j-th cell modelled as shown in Fig. 3 is obtained as

$$\left(\frac{I_{ext}}{S}\right)_{W_2} = \psi k_4 10^{\frac{\zeta_j-\zeta_i}{10}} \quad (11)$$

where,

$$k_4 = \left(\frac{r_i}{r_j}\right)^4\left(\frac{qr_i}{R}\right)^{\tau}.$$

Consequently, the total intercellular interference-to-signal ratio $\left(\frac{I_{ext}}{S}\right)_t$ for the reference user located at the same area from all surrounding cells rather than the reference cell can been calculated by integrating the above Eqs. (10) and (11) mixed with a continuous and uniform user density over a circular region approximating an hexagonal cell shown in Fig. 3 as follows

$$\left(\frac{I_{ext}}{S}\right)_t = \sum_{j=1}^{n}\left\{\iint_{(W_2)_j}\left(\frac{I_{ext}}{S}\right)_{W_2} f(N,R)dW + \iint_{(W_1)_j}\left(\frac{I_{ext}}{S}\right)_{W_1} f(N,R)dW\right\} \quad (12)$$

where, n is the total number of surrounding cells considered in the cellular mobile system as shown in Fig. 1. Substituting Eqs. (10) and (11) into (12) yields (13), i.e., $\left(\frac{I_{ext}}{S}\right)_t$ is a convex function of external cell BS's interference. We have the mean of the total intercellular interference-to-signal ratio as [4]

$$E\left[\left(\frac{I_{ext}}{S}\right)_t\right] = \frac{2\alpha N}{R^2}\sum_{j=1}^{n}\left\{\int_0^{qR} k_4 r F(\xi, r_i/r_j)dr + \int_{qR}^{R} k_3 r^{\tau+1} F(\xi, r_i/r_j)dr\right\} \quad (13)$$

where in Eq. (13), $\xi = \zeta_j - \zeta_i$ is a normal random variable have zero mean and standard deviation of σ_ξ^2 ($\sigma_\xi^2 = 2\sigma^2$) as ζ_j and ζ_i are independent fading random variables. $F(\xi, r_i/r_j)$ in the denominator of Eq. (13) can be obtained as [3], [4]

$$F(\xi, r_i/r_j) = E[\phi(\xi, r_i/r_j)10^{\xi/10}] = \int_{-\infty}^{\nu}\exp(\xi\ln 10/10)\cdot\frac{\exp(-\xi^2/2\sigma_\xi^2)}{\sqrt{2\pi\sigma_\xi^2}}d\xi \quad (14)$$

where $\phi(\xi, r_i/r_j)$ is the unit function limited by a constraint function of ν for W_1 and W_2, which accounts for the user located at the boundary between cells tending to communicate to a BS that offers the least signal attenuation, otherwise soft-handoff may occur [4]. Based on the principle and Eqs. (10) and (11), that is, $I_{ext}/S \leqq 1$, we can obtain the constraint functions as

$$\nu_{W_1} = -10\log(k_3) - 10\tau\log(r),$$
$$\nu_{W_2} = -10\log(k_4),$$

We use the similar method to the calculation of the second moment, then the variance of total intercellular interference-to-signal ratio $V[\left(\frac{I_{ext}}{S}\right)_t]$ for the same reference user can been obtained as

$$V\left[\left(\frac{I_{ext}}{S}\right)_t\right] = \sum_{j=1}^{n}\left\{\iint_{(W_2)_j} V\left[\left(\frac{I_{ext}}{S}\right)_{W_2}\right] f(N,R)dW + \iint_{(W_1)_j} V\left[\left(\frac{I_{ext}}{S}\right)_{W_1}\right] f(N,R)dW\right\} \quad (15)$$

where,

$$V\left[\left(\frac{I_{ext}}{S}\right)_{W_1}\right] = \alpha k_3^2 r^{2\tau} H(\xi, r_i/r_j) \quad (16)$$

and

$$V\left[\left(\frac{I_{ext}}{S}\right)_{W_2}\right] = \alpha k_4^2 H(\xi, r_i/r_j) \tag{17}$$

In Eqs. (16) and (17), the functions of $H(\xi, r_i/r_j)$ are

$$H(\xi, r_i/r_j) = G(\xi, r_i/r_j) - \alpha F^2(\xi, r_i/r_j) \tag{18}$$

where, $F(\xi, r_i/r_j)$ is obtained by Eq. (14). Using the same processing method which is used to obtain Eq. (14), we can obtain the equation $G(\xi, r_i/r_j)$ as

$$G(\xi, r_i/r_j) = E[\phi^2(\xi, r_i/r_j)10^{\xi/5}] = \int_{-\infty}^{\nu} \exp(\xi \ln 10/5) \cdot \frac{\exp(-\xi^2/2\sigma_\xi^2)}{\sqrt{2\pi\sigma_\xi^2}} d\xi \tag{19}$$

We substitute Eqs. (16) and (17) into Eq. (15), after some mathematical manipulations, the variance of total intercellular interference-to-signal ratio is obtained as

$$V\left[\left(\frac{I_{ext}}{S}\right)_t\right] = \frac{2\alpha N}{R^2} \sum_{j=1}^{n} \left\{ \int_{qR}^{R} k_3^2 r^{2\tau+1} H(\xi, r_i/r_j) dr + \int_0^{qR} k_4^2 H(\xi, r_i/r_j) r dr \right\} \tag{20}$$

3.2 Distribution of ISR and Optimization Issue

Based on the analysis of Sect. 3.1, we use Eqs. (9) and (13) to write the total interference-to-signal ratio, i.e., *ISR* as the sum of interference-to-signal ratio for the reference user located in the area, $qR < r_i \leqq R$ in the 0-th cell as

$$ISR = E\left[\left(\frac{I_{int}}{S}\right)_t\right] + E\left[\left(\frac{I_{ext}}{S}\right)_t\right] \tag{21}$$

In Eq. (21), the first fraction is the mean of the total intracellular interference-to-signal ratio obtained by Eq. (9). The second fraction is the mean of the total intercellular interference-to-signal ratio by Eq. (13) We can use the same method to write the ISR as the reference user located in the area of $d < r_i \leqq qR$ and the area of $0 < r_i \leqq d$ in the 0-th cell.

In order to provide uniform service to all the users and obtain the high test possible capacity, we need to optimize the power control strategy with the control parameter q and τ to ensure a uniform service. Equation (21) is also very important for analysis of the capacity, because the capacity will be chosen as the minimum value of Eq. (21). In order to obtain the highest possible capacity, we need to minimize the maximum value of Eq. (21).

During the calculation, the distribution of ISR is the curves of ISR versus r_i/R shown in Figs. 6 and 7 when the user dwells from BS to the boundary between cells. The calculation of ISR must be repeated until the uniform service is completed [2]. This process is referred as power control optimization in which ISR was numerically evaluated for the values of q to obtain that q=0.55 and 0.7 are the optimal values when τ=2 and 3 as shown in Figs. 6 and 7, this means that the high q benefits the users located in intermediate region, while the opposite condition benefits the users in the boundary. For intermediate location users, there can be considerable variation in performance, depending on the values of q and τ. On the optimal curves of *ISR*, the worst points are upper bounds of *ISR* at the power control parameter changing points, q as P1 and P2 which is termed as "hole" in Ref. [2]. We will estimate the numerical results, such as outage probability and capacity when the reference user is located at these upper bounds, with the impact of various fading parameter, σ and voice activity monitoring factor, α.

3.3 Capacity and Outage Probability

In this subsection, we develop a simple expression for a QoS indicator which we term the outage probability defined as the probability that Bit-Error-Rate (*BER*) exceeds a certain level of performance for digital communication. The received wanted signal power at the reference user located at any place of the 0-th cell is

$$S = R_b E_b$$

where, E_b is one bit-energy. *ISR* can be obtained as

$$ISR = \frac{W_{ss}}{R_b} \frac{N_0}{E_b}$$

Based on Ref. [4], E_b/N_0 must be larger than a threshold $(E_b/N_0)_{req}$ in the CDMA system. So the minimum required *ISR* is

$$\delta_{req} = \frac{R_b}{W_{ss}} \left(\frac{E_b}{N_0}\right)_{req} = \frac{1}{G} \left(\frac{E_b}{N_0}\right)_{req} \tag{22}$$

where in Eq. (22), $G = W_{ss}/R_b$. Based on Eq. (21), *ISR* can be obtained and satisfies the inequality of equation as follows [13]

$$ISR = E\left[\left(\frac{I_{int}}{S}\right)_t\right] + E\left[\left(\frac{I_{ext}}{S}\right)_t\right] \leqq \frac{1}{\delta_{req}} \tag{23}$$

Although the outage probability is defined as the probability that BER exceeds a certain level of performance for digital communication, a conventional signal-to-interference requirement is $E_b/N_0 = 7$ dB for reverse link and 5 dB for forward link as suggested in Ref. [4] for coded voice. Then calculation of the outage probability that BER exceeds a certain level reduces to the calculation of the probability that the average value of ISR exceeds the maximum required ISR as $1/\delta_{req}$ according to the criteria shown by Eq. (23). The outage probability of the reference user in the 0-th cell is given as

$$P_{out} = P_{out}\Big\{BER \geqq 10^{-3}\Big\} = P_{out}\left\{E\left[\left(\frac{I_{int}}{S}\right)_t\right] + E\left[\left(\frac{I_{ext}}{S}\right)_t\right] \geqq \frac{G}{(E_b/N_0)_{req}}\right\} = P_{out}\left\{E\left[\left(\frac{I_{ext}}{S}\right)_t\right] \geqq \kappa\right\} \quad (24)$$

Because $\frac{I_{ext}}{S}$ for one user is a Gaussian random variable, the sum of the $\frac{I_{ext}}{S}$ from a large number of users, $(\frac{I_{ext}}{S})_t$ can be approximately considered a Gaussian random variable [3]–[5] with its mean and variance given by Eqs. (13) and (20). We adopt the Gaussian approximation for simplification, so the outage probability of the reference user is described as

$$P_{out} = \frac{1}{2} erfc\left\{\frac{\kappa - E\left[\left(\frac{I_{ext}}{S}\right)_t\right]}{\sqrt{V\left[\left(\frac{I_{ext}}{S}\right)_t\right]}}\right\} \quad (25)$$

where,

$$\kappa = \frac{1}{\delta_{req}} - E\left[\left(\frac{I_{int}}{S}\right)_t\right] \quad (26)$$

is defined as the outage probability threshold of the reference user located on the line from BS to the point A in Fig. 2 in the presence of the τ-th power of distance driven. Equation (25) shows that the outage probability is determined by κ, the mean $E[(\frac{I_{ext}}{S})_t]$, and the variance $V[(\frac{I_{ext}}{S})_t]$, of intercellular interference. Based on the numerical results, the capacity is defined as the total number of users, N in the cell when the outage probability of the reference user is equal to 0.01 [3], [4].

4. Numerical Results and Discussions

In this section, we present numerical results of forward link capacity and outage probability for a CDMA cellular system. We will focus our analysis based on the protocols, IS-95 and the relative parameters listed in Table 1. Equation (21) for *ISR* and Eq. (25) for outage probability are plotted and investigated based on them.

4.1 Distribution of ISR

Equation (21) was plotted versus distance r_i for the reference user located on the line from the BS to the boundary point A between cells as shown in Fig. 2 with and without the power control strategy in Figs. 5, 6 and 7, which summarize the *ISR* distribution in the reference cell (0-th cell). The upper bound P0 shown in Fig. 5, appears when the user is at the boundary point between cells with equal power transmission for each user (without power control strategy). When the power control strategy [1] is used, the upper bound does not take place at the boundary point and occurs at the intermediate point among BS and the cell boundary. As shown in Figs. 6 and 7, service holes [2] P1 and P2 appear as a result of the power control optimization that makes ISR is due to as flat as possible.

As shown in Figs. 6 and 7, the upper bounds, P1 and P2, occurs at the power control changing points, such as where $r_i/R = q$ ($q = 0.55, \tau = 2$) for P1 and $r_i/R = q$ ($q = 0.7, \tau = 3$) for P2. In the regions of $0 \leqq r_i \leqq qR$ and $qR < r_i \leqq R$, different power equations are

Table 1 Parameter list.

Standard Deviation	σ =6, 7, 8, 9dB
Power Control	τ =2 and τ =3
Radius of Cell	R =10km
Height of BS Antenna	h_{bs}=60m
Height of MS Antenna	h_m =1.5m
Bandwidth W_{ss}	W_{ss}=1.228MHz
Bit Rate R_b	R_b= 9.6kbps
E_b/N_o	4dB,5dB,6dB,7dB,8dB,9dB
Voice Activity	α = 3/8, 1/2, 1
Carrier Frequency	F = 900MHz
Break Point d	d = 3430m

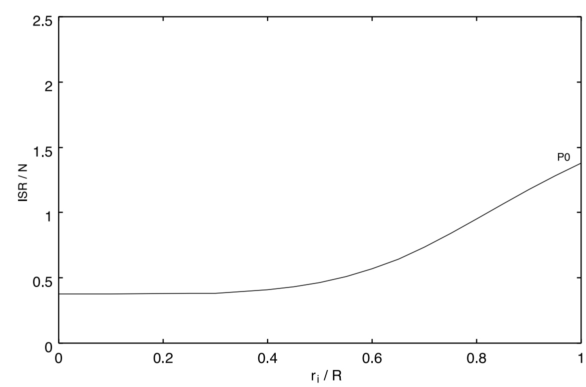

Fig. 5 *ISR* versus distance r_i/R from base station to boundary between cells without power control strategy. ($\sigma = 8$ dB, $\alpha = 3/8$, $q = 0$)

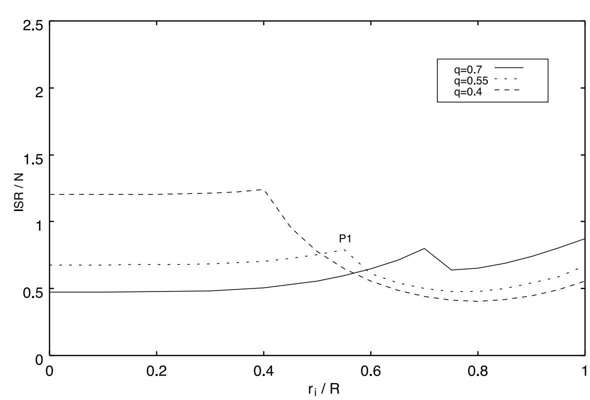

Fig. 6 *ISR* versus distance r_i/R from base station to boundary between cells with $\tau = 2$. ($\sigma = 8$ dB, $\alpha = 3/8$)

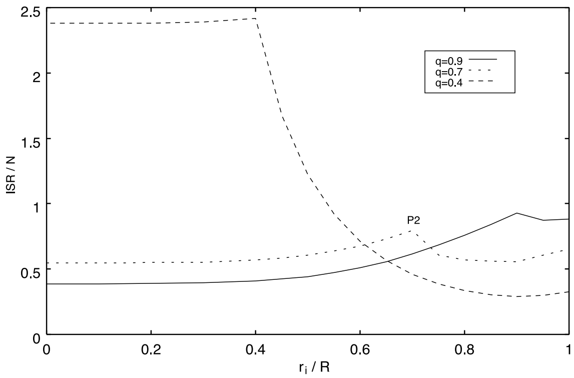

Fig. 7 *ISR* versus distance r_i/R from base station to boundary between cells with $\tau = 3$. ($\sigma = 8\,\text{dB}$, $\alpha = 3/8$)

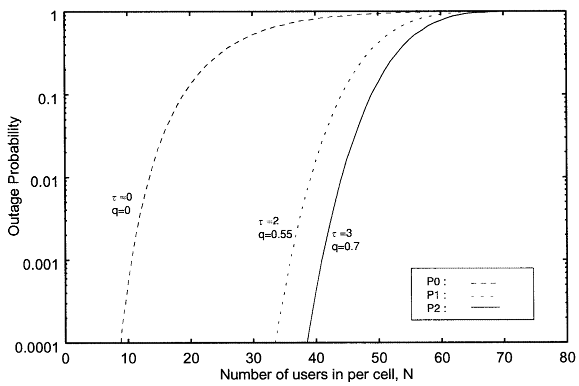

Fig. 8 Outage probability, P_{out} versus the various upper bound points P0, P1 and P2. ($\sigma = 8\,\text{dB}$, $\alpha = 3/8$)

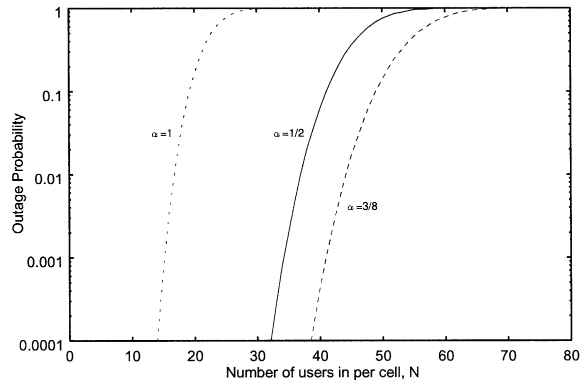

Fig. 9 Outage probability, P_{out} versus the various α at upper bound point P2. ($\sigma = 8\,\text{dB}$, $q = 0.7$, $\tau = 3$)

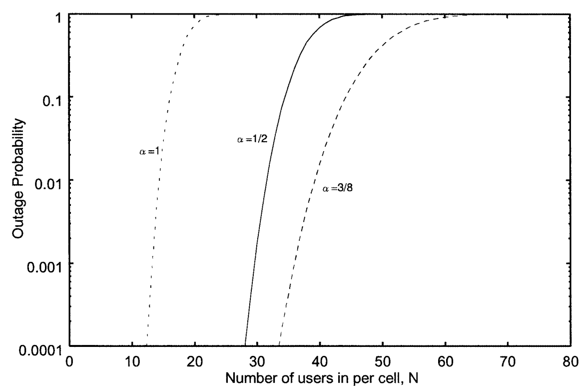

Fig. 10 Outage probability, P_{out} versus the various α at upper bound point P1. ($\sigma = 8\,\text{dB}$, $q = 0.55$, $\tau = 2$)

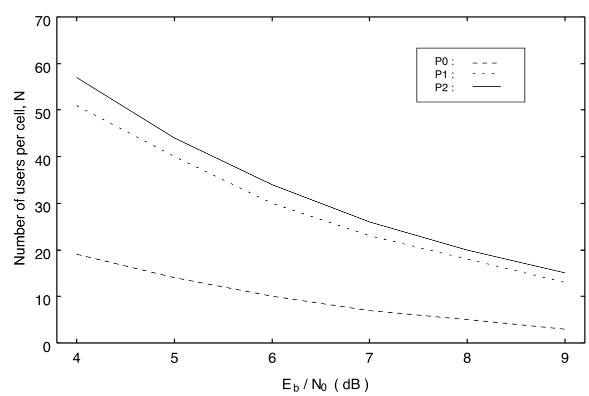

Fig. 11 Capacity versus required E_b/N_0 at upper bound points P1, P2 and P0. ($\sigma = 8\,\text{dB}$, $\alpha = 3/8$)

used as shown in Eq. (3) in order to make the curves of *ISR* as flat as possible, so the breaking points at P1 and P2 appear. Based on Figs. 6 and 7, we proved the service "hole" occurred in the intermediate region when adopting the power control strategy. In the case, it would be desirable to provide uniform service to all the users in the cell to ensure a lower value of the *ISR* at the upper bound points, P1 and P2.

4.2 Outage Probability of the "Hole" Points

Figure 8 shows the forward link outage probability for the cellular CDMA system at the upper bound points P1, P2 and P0 with and without the power control strategy. The capacity for using the power control strategy is greatly increased compared to that without power control strategy. It also shows the outage probability curves of P1 and P2 points are excellent as the cases of various power control parameter, the reason was explained that P1 and P2 were the upper bound points of the optimal curves [1], [2] which are as flat as possible and have almost the same values of the *ISR* in the two cases.

Figures 9 and 10 show the outage probability for α=3/8, 1/2 and α=1 (without voice activity monitoring) at P2 and P1. The capacity at P2 point is 43, 37 and 17 users per cell, 39, 32 and 14 users per cell at P1 point for α=3/8, 1/2 and α=1 when the outage probability is equal to 0.01 in those figures, respectively.

4.3 Capacity of the Cellular System

In Fig. 11, the capacity per cell is plotted as function of the quality requirement of a traffic type in various

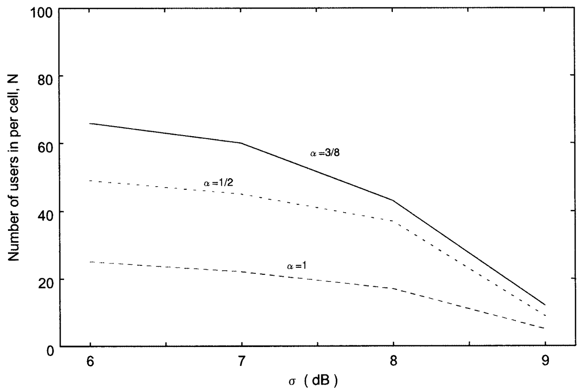

Fig. 12 Capacity versus σ at upper bound points P2 with different α.

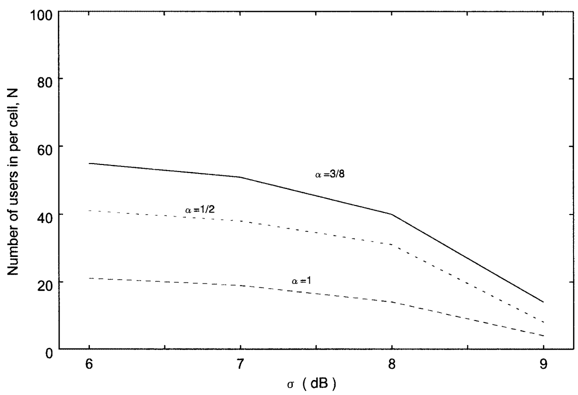

Fig. 13 Capacity versus σ at upper bound point P1 with different α.

$(E_b/N_0)_{req}$, such as the quality requirements of the voice and video are different. The capacity at P1, P2 and P0 upper bound points versus different quality requirements are estimated in detail as shown in Fig. 11, in which the capacity can be increased significantly by employing more resources or better error-control techniques with $(E_b/N_0)_{req}$.

In Figs. 12, 13 and 14, we investigated the impact of long-term fading parameter,i.e., the standard deviation σ on the capacity at upper bound point P2, P1 and P0. In practical, the long-term fading parameter, σ is from 5 dB to 10 dB. The generally accepted model about ζ whose standard deviation is $\sigma = 8$ dB for cell and $\sigma = 4$ dB for microcell which is often used in Refs. [3] and [4]. We estimate not only the situation of typical accepted model about ζ, but also the different situations with various values of σ, such as $\sigma = 6$ dB, 7 dB, and 9 dB in environments of slight and significant fading.

Figures 12 and 13 show the capacity versus fading parameter in different voice activity monitoring, α. The voice activity monitoring is real advantage of CDMA systems, which reduces mutual interference, increasing the capacity by approximately three times when α=3/8

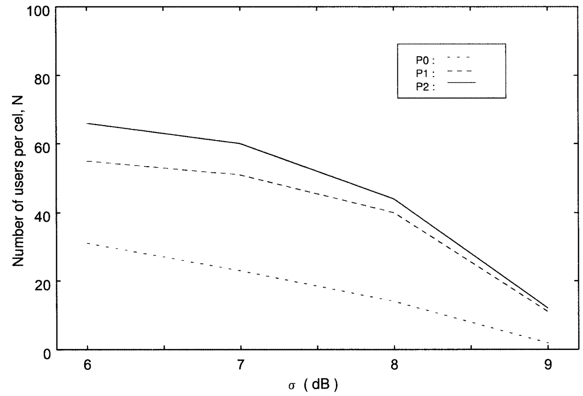

Fig. 14 Capacity versus σ at upper bound points P2, P1 and P0 when $\alpha = 3/8$

contrast to without the voice activity monitoring.

In Fig. 14, we see the capacity can be decreased significantly by increasing the standard deviation of σ whether the power control strategy is adopted or not. Based on the results shown in Fig. 14 for P2 point contrast to σ=6 dB, the deduction of user capacity is approximately 10 percents, 33 percents and 83 percents as σ is equal to 7 dB, 8 dB and 9 dB, respectively.

4.4 Discussions

As shown in this paper, a forward link power control strategy is more complicated than reverse link power control strategy because the power control with full knowledge of location of each user (the τ-th power of distance driven) or the *ISR* of each user (*ISR* Driven) is required. As a numerical example, Refs. [1] and [2] estimated the forward link capacity as shown in Fig. 1 without considering any shadow fading which in practice play an important role in wireless communication. We investigated not only impact of the power control strategy, but also estimated the situation ("hole") of optimal curve shape of the power control strategy under the fading environments in order to provide uniform service to all users distributed in the cell, furthermore at high capacity as possible. Based on Figs. 6 and 7, this purpose has been achieved contrast to Fig. 5.

In order to compare the calculation results in this chapter with Refs. [1]–[3] and [4]. All the results was motivated by IS-95 protocol and calculated using the same parameters, such as $E_b/N_0 = 5$ dB, $\sigma = 8$ dB and voice activity monitoring, α=3/8. We give the comparable results and discussions as follows.

1) Comparison of with and without power control
Based on the results reported in Refs. [1] and [2] without considering fading, a capacity of 96 users per cell was reported. Considering the fading environments, based on our results at the optimum "hole" points, we would expect a capacity of 43 users per cell and 39 users per cell at P2 and P1, respectively. For compar-

ison with the case of not using power control, we also investigated the situation, i.e., $\tau = 0$ as shown in outage probability curve of P0 in Fig. 9. We can obtain a capacity of 13 users per cell under the fading environments. Based on our calculation results, this power control strategy leads to approximately threefold the capacity at the upper bound points compared to P0 point without the power control strategy adopted in the forward link, i.e.,P1 to P0 or P2 to P0.

2) Comparison of theoretical and simulation results
In comparison with the *ISR* Driven power control strategy reported in Refs. [3] and [4], the results obtained by a computer simulation using Monte Carlo method were estimated by Gillhousen et al. Considering practical long-term fading environments, it is clear that the capacity increases to 38 users per cell by introducing the *ISR* Driven power control strategy. Under the same fading environments, we theoretically calculated the situation of forward link by introducing the τ-th power of distance driven control strategy and obtained the optimum results at P1 and P2, such as capacity of 39 users per cell and 43 users per cell, respectively. In summary, the simulation [3], [4] and the theoretical results calculated in this paper are based upon the more practical propagation models and the fading environments, which prove the validity of them. This theoretical analysis is validated against the simple analytical models proposed in Refs. [1] and [2] under non-fading environments or Ref. [5] without power control strategy.

5. Conclusions

This paper has presented a theoretical analysis of forward link in CDMA cellular systems by introducing the τ-th power of distance driven control strategy. The performance of the *FLPCS* on the cellular systems can be summarized as follows.

1) The forward link power control in CDMA cellular systems may lead to a service "hole" which means selection of power control parameter or allocation of transmission power must be carefully considered in order to achieve high capacity.

2) Based on our results, the upper bounds of *ISR* are just the lower bounds of capacity based on the optimal shape for the power control strategy. One can see that power control leads to approximately threefold the capacity compared to the upper bound (P0 point) in the presence of no power control.

3) Based on our results as shown in Fig. 14, we give the numerical results about effects of various fading environments on CDMA cellular system. It shows that the fading will play an important role on the performance of wireless mobile communication. It can be concluded that the forward link without power control strategy is a very heavy restriction for the user capacity of the CDMA system, especially in environments of significant fading.

Finally, the techniques and processing methods described in this paper could easily be extended to treat the hierarchical macrocell/microcell architectures which have drawn much attention all over the world recently. They are also applicable for investigating the throughput and designing the burst admission schemes of integrated services in wireless cellular systems.

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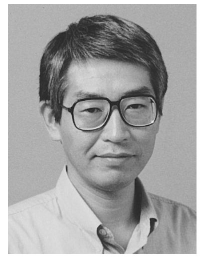

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