

PAPER

Performance Analysis of a DS-CDMA Cellular System with Cell Splitting into Macrocell and Microcell Architecture*

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SUMMARY The demand for wireless mobile communications has grown at a very high rate, recently. In order to solve the non-uniform traffic rates, the use of cell splits is unavoidable for balancing the traffic rate and maximizing total system capacity. For cell planning, a DS-CDMA cellular system can be comprise of different cell sizes because of different demands and population density of the service area. In this paper, we develop a general model to study the forward link capacity and outage probability of a DS-CDMA cellular system with mixed cell sizes. The analysis of outage probability is carried out using the log-normal approximation. When a macrocell is split into the three microcells, as an example, we calculate the multi-cross interferences between macrocells and microcells, and the forward link capacities for the microcells and the neighboring macrocells. The maximum allowable capacity plane for macrocell and microcell is also investigated. The numerical results and discussions with previous published results of reverse link are summarized.
key words: *system capacity, outage probability, capacity plane, code division multiple access(CDMA), macrocell and microcell*

1. Introduction

The Direct Sequence Code Division Multiple Access (DS-CDMA) system has been proved to have definite advantages in various respects such as multi-path fading mitigation, interference suppression and larger capacity [1]–[3]. Especially, the future wide band DS-CDMA systems are expected to provide various types of applications besides the traditional voice service. These applications include transmissions of text messages, images, web pages, audio and video streams, to name a few. Several system level problems, such as admission strategy, quality of service (QoS) guarantee, burst scheduling, etc., arise in these wireless systems.

In order to meet the level of demands, several solutions have been proposed and adopted. One of the obvious solutions is to structure the cellular architec-

ture with cell splitting into macrocell, microcell and picocell. To solve the non-uniform traffic rates and non-uniform user distribution, cell splits in macrocell and microcell architectures are unavoidable to be used for balancing the traffic rate and maximizing total system capacity by several methods, such as smart antennas with switch beam [4], adaptive array systems [5] and soft boundary design [6].

In cellular systems, macrocell and microcell sizes are determined based on the traffic load and population density of the service area. In heavily populated areas, cell splits with many microcells are unavoidable to increase the total system capacity. After cell splitting, heavily populated areas are with microcell structure, the other areas are with macrocell structure. Then the cellular system is configured with cells of mixed sizes. In cellular systems with a uniform cell size, all the cells are in the identical condition and the interferences received by individual cells are equal [3], [4]. In cellular systems with mixed cell sizes, however, each macrocell and microcell have different cell sizes and the surrounding cells and the interferences received by individual cells are different each other. Then, each cell will have different characteristics and researches on them become very significant.

For the reverse link, the power control is assumed as the perfect power control [3], [4] in order to solve the near-far problem [4] and the cell splitting [1], [5] and hierarchical structures [12], [13] are adopted to solve the problems of the non-uniform traffic rates and user distribution. Considering the difference between the reverse and forward links, the investigated target of the reverse link is the base station which is fixed at the center of the cell. On the other hand, the target of the forward link is the mobile station which may be located at any positions of the cell. Therefore the perfect power control of the reverse link and its analysis methods can not be applied to the forward link [4] directly.

In spite of the vast literature on DS-CDMA cellular system, the capacity plane and outage probability of the forward link in a DS-CDMA cellular system with cell splitting into macrocell and microcell have not been evaluated so far. In this paper, we develop a general model to study the forward link capacity and outage

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probability of a DS-CDMA cellular system with mixed cell sizes. The analysis of outage probability is carried out using the log-normal approximation. When a macrocell is split into the three microcells, as an example, we calculate the multi-cross interferences between macrocells and microcells, and the forward link capacities for the microcells and the neighboring macrocells. The maximum allowable capacity plane for macrocell and microcell is also investigated. The numerical results and discussions with previous published results of reverse link are summarized.

This paper is organized as follows. The assumptions concerning the propagation method and system description are given in Sect.2. The overall analytical method of obtaining various types of interference is derived in Sect.3. In Sect.4 and Sect.5, the system performance evaluation methods and numerical results are discussed, respectively. Finally, in Sect.6 the main points are summarized.

2. System Description and Propagation Model

We consider the general cellular architecture with uniform hexagonal cell (macrocell) as shown in Fig. 1. The 0-th macrocell is considered to be split into three microcells as shown in Fig. 2 where one is the one-third of the macrocell (microcell). Both macrocell and microcell BSs are located at the center of the cells. Because of the symmetry of cellular system architecture, we set the macrocell BS of reference cell as the 0-th BS and the microcell BS of reference cell as the 01-th BS. As shown in Fig. 1, we defined D_j is the distance between the 0-th BS and j -th surrounding cell BS. r_0^{mac} is the distance between the reference mobile station (MS) of macrocell and its base station (BS). r_j^{mac} is the distance between the reference MS and j -th surrounding cell BS. In Fig. 2, r_0^{mic} is the distance of the reference MS of microcell and its BS. r_j^{mic} is the distance between the reference MS and j -th surrounding cell BS. In the case of the microcell, we also can calculate the distances between macrocell BS and microcell BS, and so forth.

The mobile radio channel attenuation is subject to fast fluctuation around a slowly varying mean value. We assume that the short-term fluctuations caused by multi-path propagation can be mitigated by using diversity and error control techniques [3],[4]. Hence, our propagation model only considers slow variations caused by the shadowing fading. These variations occur when the envelope of the received signal is shadowed by obstructions such as hills and buildings [1]. Therefore, our link gain given the location of the MS, g^2 , is

$$g^2 = r^{-\alpha} 10^{\lambda/10} \tag{1}$$

where r is the distance between MS and BS, α is the path loss exponent, and λ is the attenuation in dB due to shadowing, with zero mean and standard deviation

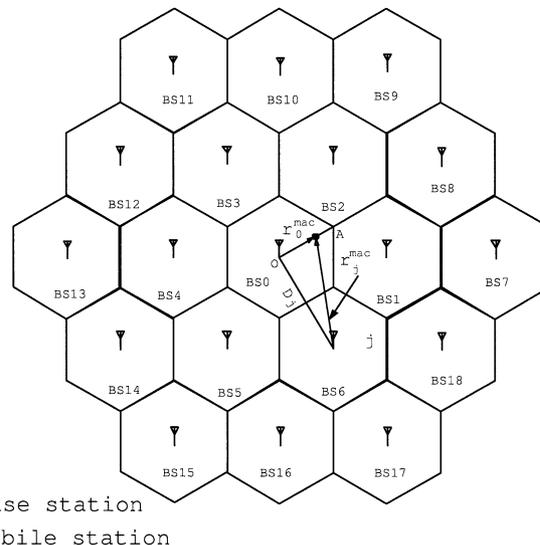


Fig. 1 Cellular system architecture [2], [6].

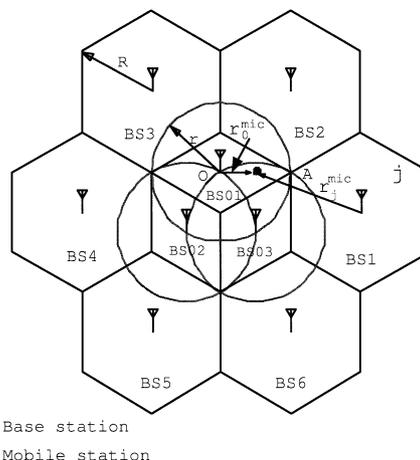


Fig. 2 A DS-CDMA cellular system with mixed cell sizes.

σ^2 . Any analysis of other cell interference involves comparison of propagation losses among two or more base stations. Thus, the model must consider the dependence of the propagation losses from a mobile user to two different base stations [15]. We may express the random component of decibel loss as the sum components: one in the near field of user that is common to all base stations, and one that pertains solely to the receiving base station and is independent from one base station to another. Thus, we may express the random component of decibel loss for i -th base station ($i = 0, 1, 2, \dots$) as [13], [15]

$$\lambda_i = a\delta + b\delta_i, \text{ where } a^2 + b^2 = 1 \tag{2}$$

with $E(\lambda_i) = E(\delta) = E(\delta_i) = 0$, $Var(\lambda_i) = Var(\delta) = Var(\delta_i) = \sigma^2$ and $E(\delta\delta_i) = 0$ for all i , and $E(\delta_i\delta_j) = 0$ for all $i \neq j$. Thus, the normalized covariance (correlation coefficient) of the losses to two base stations, i and j , is [15]

$$\frac{E(\lambda_i \lambda_j)}{\sigma^2} = a^2 = 1 - b^2 \quad (i \neq j)$$

We may reasonably assume that the near-field and base station-specific propagation uncertainties have the equal standard deviations that means $Var(a\delta) = Var(b\delta_i)$. In that case, $a^2 = b^2 = 1/2$.

3. Interference Analysis

3.1 Cellular System with Uniform Cells

A. Intracellular Interference

If each *BS* transmits a total power of P_T to all of its mobiles and if the same power is allocated to all N traffic channels and the pilot channel on the forward link [6]–[8], then the signal power at the output of matched filter of the reference MS is represented as

$$S = \frac{g_0^2 P_T}{N+1} \quad (3)$$

and the additive white Gaussian noise (AWGN)-to-signal ratio is

$$\eta/S = \frac{N_0 W}{S} \quad (4)$$

where N_0 is the signal-sided power spectral density of AWGN and W is the allocated bandwidth.

Although the pilot channel was mentioned, its impact on the system is not considered in the intracellular interference and intercellular interference calculation. We count the intracellular interference by $i = 1, 2, 3 \dots N$ only considering the traffic channels, although strictly speaking, for the N channels, each user demodulator processes a composite received waveform containing the desired signal and $N - 1$ interfering signals [4] that means $i = 1, 2, 3 \dots N$ (generally $N \gg 1$ [6]). Then the average mean of intracellular interference-to-signal ratio, $E[I_{int}/S]$ from other channels in the same cell is

$$E\left[\frac{I_{int}}{S}\right] = E\left[\frac{1}{S} \sum_{i=1}^N v_i \frac{g_0^2 P_T}{N+1}\right] = \sum_{i=1}^N E[v_i] \quad (5)$$

where v is the random variable to represent the voice activity variable. The random variable v is represented as [5]

$$v = \begin{cases} 1 & \text{for probability } \theta \\ 0 & \text{for probability } 1 - \theta \end{cases} \quad (6)$$

where, θ is also termed as voice activity factor (VAF) [4], [5].

B. Intercellular Interference

According to Sect. 3.1(A), in calculation of the intercellular interference generated from the other surrounding cells, only traffic channels are considered as

intercellular interference [6]. We follow the same process as that in Ref. [6], the average mean of intercellular interference-to-signal ratio from the external J surrounding BSs is [4]–[6]

$$\begin{aligned} E\left[\frac{I_{ext}}{S}\right] &= E\left[\frac{1}{S} \sum_{j=1}^J \sum_{i=1}^N v_{ij} \frac{g_j^2 P_T}{N+1}\right] \\ &= E\left[\sum_{j=1}^J \sum_{i=1}^N v_{ij} \frac{g_j^2}{g_0^2}\right] \\ &= \sum_{j=1}^J \sum_{i=1}^N E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^\alpha \\ &\quad \cdot E\left[\phi_j\left(\zeta_j, \frac{r_0^{mac}}{r_j^{mac}}\right) 10^{\zeta_j/10}\right] \end{aligned} \quad (7)$$

Here, ζ_j is $\lambda_j - \lambda_0$ and has a standard deviation of $\sqrt{2}\sigma$, and λ_j and λ_0 are two independent variables. J is the total number of surrounding cells considered in this calculation and the mean of $\phi_j(\zeta_j, r_0^{mac}/r_j^{mac}) 10^{\zeta_j/10}$ is represented as $E[\Phi]$ that can be calculated as [1], [4]

$$\begin{aligned} E\left[\phi_j\left(\zeta_j, \frac{r_0^{mac}}{r_j^{mac}}\right) 10^{\zeta_j/10}\right] &= E[\Phi] = \exp\left(\frac{\sigma \ln(10)}{10}\right)^2 \\ &\quad \cdot \left(1 - Q\left[\frac{10\alpha \log\left(\frac{r_j^{mac}}{r_0^{mac}}\right) - \frac{\sqrt{2} \ln(10)\sigma}{10}}{\sqrt{2}\sigma}\right]\right) \end{aligned} \quad (8)$$

where $Q(x) = 1/\sqrt{2\pi} \int_x^\infty e^{-y^2/2} dy$ and $\phi_j(\zeta_j, r_0^{mac}/r_j^{mac})$ is a constraint function. It account users for mobiles at boundaries trying to communicate with a particular *BS* that offers the least signal attenuation under shadow fading conditions to respective mobiles. It is represented as [5], [6]

$$\phi_j\left(\zeta_j, \frac{r_0^{mac}}{r_j^{mac}}\right) = \begin{cases} 1 & \text{for } \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^\alpha 10^{\zeta_j/10} \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

In order to investigate the system outage probability, we have to calculate the second moment that is the variance. After simply derivation, the variance of the interference-to-signal ratio for mobile user can be obtained as follows [5], [6]

$$Var\left[\frac{I_{ext}}{S}\right] = \left(\frac{r}{R}\right)^{-2\alpha} \sum_{j=1}^J \sum_{i=1}^N E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^{2\alpha} H(\cdot) \quad (10)$$

In above equation, the function of $H(\cdot)$ is [4], [5]

$$H(\cdot) = E[\Phi^2] - E[v_{ij}]E[\Phi] \quad (11)$$

where, $E[\Phi]$ is obtained by Eq. (8). Using the similar

processing method which is used to obtain Eq. (8), we can get the equation $E[\Phi^2]$ as follows [4]

$$E\left[\phi_j^2\left(\zeta_j, \frac{r_0^{mac}}{r_j^{mac}}\right)10^{\zeta_j/5}\right] = E[\Phi^2] = \exp\left(\frac{\sigma \ln(10)}{5}\right)^2 \cdot \left(1 - Q\left[\frac{10\alpha \log\left(\frac{r_j^{mac}}{r_0^{mac}}\right) - \frac{\sqrt{2} \ln(10)\sigma}{5}}{\sqrt{2}\sigma}\right]\right) \quad (12)$$

3.2 Cellular System with Mixed Cells

In a uniform cell size environment derived in above section, individual cell has identical $E[I_{ext}/S]$ and $Var[I_{ext}/S]$ since every cell is in the same condition, such as path loss exponent, shadowing loss and the same size of cell. In a cellular system with mixed cells, however, the individual cell does not have the same cell size and the outside environment and receives a distinct amount of interference from out cell. Furthermore, due to different cell size, each cell should have a different required power and a different received signal power S , such as S_R for macrocell and S_r for microcell used in this paper. Thus, each cell has different values of $E[I_{ext}/S]$ and $Var[I_{ext}/S]$ from the other cells. In order to investigate the system capacity and the impact of each other, we should know $E[I_{ext}/S]$ and $Var[I_{ext}/S]$ for macrocell and microcell, respectively. Although practical DS-CDMA cellular system may consists of many cell splitting according to the wireless environments and the service demands, as a analytical example for mixed cell size, we considered the simple system as shown in Fig. 2, where center macrocell BS_0 is split into three microcells (BS_{01} , BS_{02} and BS_{03}) and the new cell base stations are located at the center of these microcells. In order to investigate this system, first, we have to define the power control ratio between macrocell and microcell, and the multi-cross interference.

A. Power Control Ratio

Considering two adjacent cells with different cell sizes; the size of the microcell is r , and that of the macrocell is R . Imagine a mobile user is located at the boundary between the microcell and the macrocell. If the mobile user belonging to macrocell j is located at the cell boundary, the received signal power S_j can be expressed as

$$S_j = \frac{P_{TR}}{(N_R + 1)R^\alpha} 10^{-\lambda_j/10} \quad (13)$$

where P_{TR} is the total power of macrocell and N_R is the total number of mobile users in this cell. R and λ_j are the radius of this cell j and the corresponding shadowing variable (zero mean and σ_j^2 dB standard deviation), respectively.

From Eq. (13), we obtain

$$10 \log S_j = 10 \log \frac{P_{TR}}{(N_R + 1)} - 10\alpha \log R - \lambda_j \quad (14)$$

Since the standard deviation of $10 \log \frac{P_{TR}}{(N_R + 1)}$ is 0 dB, it is clear that $10 \log S_j$ is a Gaussian random variable with a mean of $10 \log \frac{P_{TR}}{(N_R + 1)} - 10\alpha \log R$ and a standard deviation of σ_j^2 dB.

In a similar manner, the received signal power if the mobile user belonging to microcell i is located at the cell boundary, S_i can be expressed as

$$10 \log S_i = 10 \log \frac{P_{Tr}}{(N_r + 1)} - 10\alpha \log r - \lambda_i \quad (15)$$

Here, P_{Tr} is the total power of microcell and N_r is the total number of mobile users in this cell. r and λ_i are the radius of this cell i and the corresponding shadowing variable (zero mean and σ_i^2 dB standard deviation), respectively.

The logarithmic ratio of S_j to S_i is

$$10 \log \frac{S_j}{S_i} = 10 \log \frac{P_{TR}(N_r + 1)}{P_{Tr}(N_R + 1)} + 10\alpha \log \frac{r}{R} + (\lambda_i - \lambda_j) \quad (16)$$

If λ_i and λ_j are assumed to have an equal probability distribution and its average value is considered, then $\frac{S_j}{S_i}$ can be simplified to

$$E\left[\frac{S_j}{S_i}\right] = \frac{P_{TR}(N_r + 1)}{P_{Tr}(N_R + 1)} \left(\frac{r}{R}\right)^\alpha \quad (17)$$

A cell size in a DS-CDMA cellular system is mainly determined by the path loss and the the signal power transmitted. According to references [4] and [5] about the cell boundary condition for reverse and forward links shown in Fig. 3, it is reasonable that $E\left[\frac{S_i}{S_r}\right] = 1$ at the boundary when we determine the total power allocation P_{TR} for macrocell and P_{Tr} for microcell. Then the power control ratio, $\frac{P_{TR}}{P_{Tr}}$ will become as

$$\frac{P_{TR}}{P_{Tr}} = \left(\frac{r}{R}\right)^{-\alpha} \frac{N_R + 1}{N_r + 1} \quad (18)$$

B. Multi-cross Interference for a Micro Cell

As shown in Fig. 2, because of the symmetry of the cellular architecture, here we consider BS_{01} as the reference microcell. According to the same derivation described in Sect. 3, the intracellular interference-to-signal ratio from other channels in the microcell, $E[I_{int}/S_r]$, is represented as

$$E\left[\frac{I_{int}}{S_r}\right] = E\left[\frac{1}{S_r} \sum_{i=1}^{N_r} v_i \frac{g_0^2 P_{Tr}}{N_r + 1}\right] = \sum_{i=1}^{N_r} E[v_i] \quad (19)$$

Since the mobile user in BS_{01} receives interference not only from two neighboring microcells at BS_{02} and BS_{03} but also from J outer cells of the first and second tiered

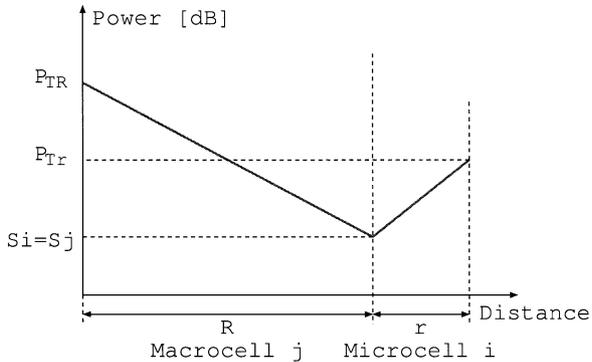


Fig. 3 Cell boundary condition and balancing for forward link [4], [5].

macrocells, the intercellular interference-to-signal ratio from these relevant external cells, I_{ext}/S_r , is represented as

$$\begin{aligned} \frac{I_{ext}}{S_r} &= \frac{1}{S_r} \sum_{j=2}^3 \sum_{i=1}^{N_r} v_{ij} \frac{g_j^2 P_{Tr}}{N_r + 1} \\ &+ \frac{1}{S_r} \sum_{j=1}^6 \sum_{i=1}^{N_R} v_{ij} \frac{g_j^2 P_{TR}}{N_R + 1} \\ &+ \frac{1}{S_r} \sum_{j=7}^J \sum_{i=1}^{N_C} v_{ij} \frac{g_j^2 P_{TC}}{N_C + 1} \end{aligned} \quad (20)$$

Here, N_C is the total number of mobile users in the macrocell located at the second tier and P_{TC} is the total power of the macrocell. If use the same manipulation shown in Sect. 3.2(A), we can obtain the power control ratio like Eq. (18) as $\frac{P_{TC}}{P_{Tr}} = \left(\frac{r}{R}\right)^{-\alpha} \frac{N_C + 1}{N_r + 1}$ and $\frac{P_{TC}}{P_{TR}} = \frac{N_C + 1}{N_R + 1}$. Combining Eq. (8) with Eq. (20) and considering the power control ratio between macrocell and microcell, one obtains the average mean of I_{ext}/S_r as

$$\begin{aligned} E\left[\frac{I_{ext}}{S_r}\right] &= \sum_{j=2}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^\alpha E[\Phi] \\ &+ \left(\frac{r}{R}\right)^{-\alpha} \sum_{j=1}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^\alpha E[\Phi] \\ &+ \left(\frac{r}{R}\right)^{-\alpha} \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^\alpha E[\Phi] \end{aligned} \quad (21)$$

In order to investigate the system outage probability, we have to calculate the second moment that is the variance. Based on the calculation method in Ref. [4], then the variance of the intercellular interference-to-signal ratio for mobile user can be obtained as follows

$$\text{Var}\left[\frac{I_{ext}}{S_r}\right] = \sum_{j=2}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^{2\alpha} H(\cdot)$$

$$\begin{aligned} &+ \left(\frac{r}{R}\right)^{-2\alpha} \sum_{j=1}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^{2\alpha} H(\cdot) \\ &+ \left(\frac{r}{R}\right)^{-2\alpha} \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}}\right)^{2\alpha} H(\cdot) \end{aligned} \quad (22)$$

In above equation, the function of $H(\cdot)$ has been obtained by Eq. (11).

C. Interference for the First Tiered Macro Cells

Using the same similar manner, the intracellular interference-to-signal ratio from other channels a first tiered macrocell, $E[I_{int}/S_R]$, is estimated as same as before, and is expressed by

$$E\left[\frac{I_{int}}{S_R}\right] = E\left[\frac{1}{S_R} \sum_{i=1}^{N_R} v_i \frac{g_0^2 P_{TR}}{N_R + 1}\right] = \sum_{i=1}^{N_R} E[v_i] \quad (23)$$

Since the mobile station in BS_j receives interference not only from three neighboring microcells but also from the J outer macrocells, the intercellular interference-to-signal ratio from these relevant external cells, I_{ext}/S_R , is represented as

$$\begin{aligned} \frac{I_{ext}}{S_R} &= \frac{1}{S_R} \sum_{j=1}^3 \sum_{i=1}^{N_r} v_{ij} \frac{g_j^2 P_{Tr}}{N_r + 1} \\ &+ \frac{1}{S_R} \sum_{j=2}^6 \sum_{i=1}^{N_R} v_{ij} \frac{g_j^2 P_{TR}}{N_R + 1} \\ &+ \frac{1}{S_R} \sum_{j=7}^J \sum_{i=1}^{N_C} v_{ij} \frac{g_j^2 P_{TC}}{N_C + 1} \end{aligned} \quad (24)$$

Combining Eq. (8) with Eq. (24) and considering the power control ratio, one gets the average mean of I_{ext}/S_R as follows

$$\begin{aligned} E\left[\frac{I_{ext}}{S_R}\right] &= \left(\frac{r}{R}\right)^\alpha \sum_{j=1}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^\alpha E[\Phi] \\ &+ \sum_{j=2}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^\alpha E[\Phi] \\ &+ \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^\alpha E[\Phi] \end{aligned} \quad (25)$$

Based on the same method described in Sect. 3.2(B), one can get the variance of the intercellular interference-to-signal ratio for macrocell as

$$\begin{aligned} \text{Var}\left[\frac{I_{ext}}{S_R}\right] &= \left(\frac{r}{R}\right)^{2\alpha} \sum_{j=1}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^{2\alpha} H[\cdot] \\ &+ \sum_{j=2}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}}\right)^{2\alpha} H[\cdot] \end{aligned}$$

$$+ \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}} \right)^{2\alpha} H[\cdot] \quad (26)$$

where, $H(\cdot)$ has been given by Eq. (11).

4. Performance Analysis

4.1 Capacity Plane

We consider the capacity plane investigated in Refs. [12] and [13] for the case of the DS-CDMA cellular system with mixed cell size. In this system, when intracellular and intercellular interference exist, the bit-energy to interference power spectral density (PSD) ratio $\frac{E_b}{I_0}$ can be expressed as [4], [5]

$$\begin{aligned} \frac{E_b}{I_0} &= \frac{S/R}{(I_{int} + I_{ext} + N_0W)/W} \\ &= \frac{W/R}{I_{int}/S + I_{ext}/S + \eta/S} \\ &= \frac{G_s}{I_{int}/S + I_{ext}/S + \eta/S} \end{aligned} \quad (27)$$

From this formula, DS-CDMA bit-energy to interference PSD ratio can be expressed as follow.

For microcell,

$$\frac{E_b}{I_0} = \frac{G_s}{E[\frac{I_{int}}{S_r}] + E[\frac{I_{ext}}{S_r}] + E[\frac{N_0}{S_r}]} \quad (28)$$

And for macrocell,

$$\frac{E_b}{I_0} = \frac{G_s}{E[\frac{I_{int}}{S_R}] + E[\frac{I_{ext}}{S_R}] + E[\frac{N_0}{S_R}]} \quad (29)$$

where G_s is processing gain of the system.

To guarantee that bit-energy to interference PSD ratio for both macrocell and microcell always satisfies the required bit-energy to interference PSD ratio, we have

$$\frac{E_b}{I_0} \geq \left(\frac{E_b}{I_0} \right)_{req} \quad (30)$$

Substituting Eqs. (19) and (21) into Eq. (30), and adding the additive white Gaussian noise, we obtain the requirement formula for microcell as

$$\begin{aligned} &\sum_{i=1}^{N_r} E[v_i] + \sum_{j=2}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}} \right)^\alpha E[\Phi] \\ &+ \left(\frac{r}{R} \right)^{-\alpha} \sum_{j=1}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}} \right)^\alpha E[\Phi] \\ &+ \left(\frac{r}{R} \right)^{-\alpha} \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mic}}{r_j^{mic}} \right)^\alpha E[\Phi] \end{aligned}$$

$$\leq G_s \left(\frac{E_b}{I_0} \right)_{req}^{-1} - \frac{\eta}{S} \quad (31)$$

For macrocell, we substitute Eqs. (23) and (25) into Eq. (30), and adding the additive white Gaussian noise, the requirement formula is

$$\begin{aligned} &\sum_{i=1}^{N_R} E[v_i] + \left(\frac{r}{R} \right)^\alpha \sum_{j=1}^3 \sum_{i=1}^{N_r} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}} \right)^\alpha E[\Phi] \\ &+ \sum_{j=2}^6 \sum_{i=1}^{N_R} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}} \right)^\alpha E[\Phi] \\ &+ \sum_{j=7}^J \sum_{i=1}^{N_C} E[v_{ij}] \left(\frac{r_0^{mac}}{r_j^{mac}} \right)^\alpha E[\Phi] \\ &\leq G_s \left(\frac{E_b}{I_0} \right)_{req}^{-1} - \frac{\eta}{S} \end{aligned} \quad (32)$$

From Eqs. (31) and (32), we can obtain the allowable maximum capacity plane region that satisfies both demand of bit-energy to interference PSD ratio.

4.2 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. Based on the description in the section 4.1 (Eq. (30)), the total interference-to-signal ratio, ISR must satisfies the inequality of equation as follows [3], [4]

$$\frac{I_{int}}{S} + \frac{I_{ext}}{S} + \frac{\eta}{S} \leq \frac{1}{\delta_{req}}, \quad (33)$$

where,

$$\delta_{req} = \frac{1}{G_s} \left(\frac{E_b}{I_0} \right)_{req}$$

Although the outage probability is defined as the probability that BER exceeds a certain level of performance for digital communication, a conventional required bit-energy to interference PSD ratio is $(E_b/I_0)_{req} = 7$ dB for forward link as suggested in Ref. [6] 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 the total interference-to-signal ratio exceeds the maximum required value as $1/\delta_{req}$ according to the criteria shown by Eq. (33). The outage probability of the user is given as [1], [2]

$$P_{out} = P_{out} \left\{ BER \geq 10^{-3} \right\}$$

$$\begin{aligned}
 &= P_{out} \left\{ \frac{I_{int}}{S} + \frac{I_{ext}}{S} + \frac{\eta}{S} \geq \frac{G_s}{(E_b/I_0)_{req}} \right\} \\
 &= P_{out} \left\{ \sum_{i=1}^N v_i + \frac{I_{ext}}{S} + \frac{\eta}{S} \geq \frac{1}{\delta_{req}} \right\} \quad (34)
 \end{aligned}$$

where $\sum_{i=1}^N v_i$ is calculated and presented by its average mean, $N \cdot \theta$. Since the random variable $\frac{I_{ext}}{S}$ can be approximately considered a Gaussian random variable [3]–[5] with its mean and variance given by Eqs. (21) and (22) for microcell, and Eqs. (25) and (26) for macrocell, respectively. All variables are assumed as mutually independent, and we adopt the log-normal approximation for simplification, so the outage probability, Eq. (28) is described as [3], [4]

$$P_{out} = \frac{1}{2} \operatorname{erfc} \left\{ \frac{\kappa - E[\frac{I_{ext}}{S}]}{\sqrt{\operatorname{Var}[\frac{I_{ext}}{S}]}} \right\} \quad (35)$$

where,

$$\kappa = \frac{1}{\delta_{req}} - \frac{\eta}{S} - N \cdot \theta \quad (36)$$

is defined as the outage probability threshold of the reference user located on the line from *BS* to the cell boundary. Eq. (35) shows that the outage probability is determined by κ , the mean $E[\frac{I_{ext}}{S}]$, and the variance $V[\frac{I_{ext}}{S}]$, of intercellular interference. According to Refs. [1] and [4], the system capacity is usually defined as the maximum number of mobile users per cell that the outage probability is equal to 0.01.

5. Numerical Results

In this section, we will present numerical results for the calculation developed previously. Values of the following parameters are well accepted and are usually assumed for numerical evaluations.

- (a) VAF θ : voice activity factor, 3/8 and 1/2
- (b) G_s : processing gain, 21 dB
- (c) S/η : signal to white Gaussian noise, 20 dB
- (d) r/R : ratio of the micro cell radius to the macro cell radius, $\sqrt{3}/2$
- (e) $(E_b/I_0)_{req}$: bit energy-to-interference density ratio, 7 dB
- (f) α : path-loss exponent, 4
- (g) σ^2 : standard deviation of λ , 8 dB
- (h) J : total number of surrounding cells, 18

A. Capacity Plane and Outage Probability

In this subsection, we present numerical results for the capacity plane and outage probability of the DS-CDMA cellular system with cell splitting into macrocell and microcell architecture. According to the required $(E_b/I_0)_{req} = 7$ dB and the constraint inequalities (Eqs. (31) and (32)), the maximum allowable capacity plane regions are plotted in Fig. 4. *AEB* and

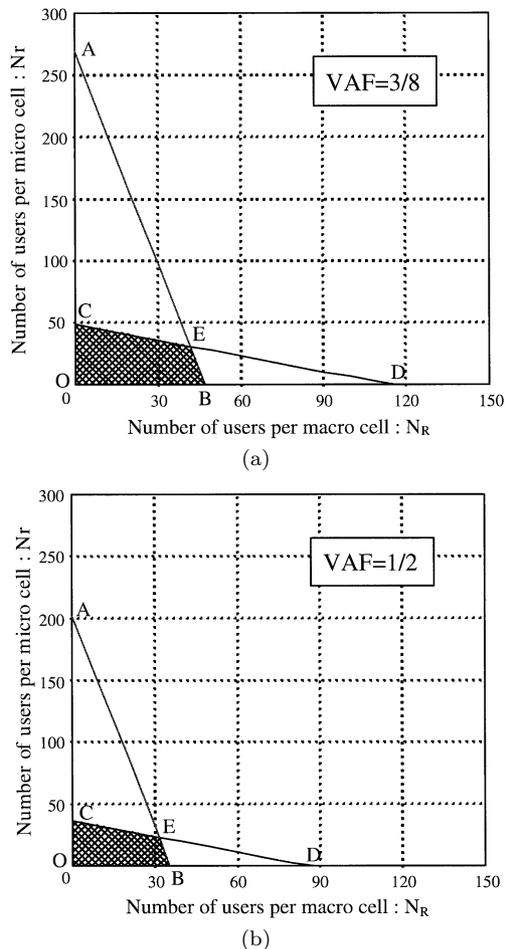


Fig. 4 Maximum allowable capacity plane region (Hatched areas) between N_r and N_R (a) VAF $\theta=3/8$ (b) VAF $\theta=1/2$ ($G_s = 21$ dB, $S/\eta = 20$ dB, $\alpha = 4$, $\sigma = 8$ dB and $N_R = N_C$).

CED curves are macrocell constraint and microcell constraint, respectively. the shaded part *OBEC* is the maximum allowable capacity plane regions, in which both the required $(E_b/I_0)_{req}$ for macrocell and microcell are satisfied, simultaneously. In particular, we are going to focus our discussion on the cross point E. In Fig. 4(a), (N_r, N_R) is (31,41) at point E, and in Fig. 4(b) it is (27,31). At these points, they are suitable to be used in balancing traffic rate and also maximizing the system capacity.

Figures 5 and 6 show the outage probability of macrocell and microcell when reference user is located at the boundary between the cells. Then the results are the lower bounds that means if the reference user is located in the medium of cell, the better results will be obtained. For microcell, Eq. (35) is plotted for VAF $\theta = 3/8$ and $G_s = 21$ dB, as the leftmost curve of Fig. 5. The rightmost curve applies to the situation that all cells other than the desired user’s cells are on the average loaded less heavily, such as 1/4 total load of surrounding cells. For macrocell, Eq. (29) is plotted in Fig. 6. From Figs. 5 and 6, one can see that the per-

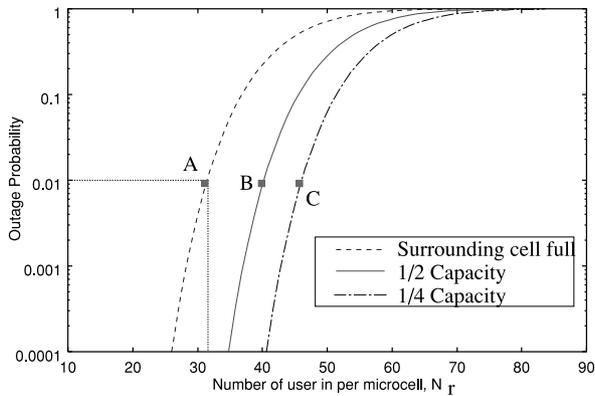


Fig. 5 Outage probability of microcell with various loads of surrounding cells and VAF $\theta=3/8$.

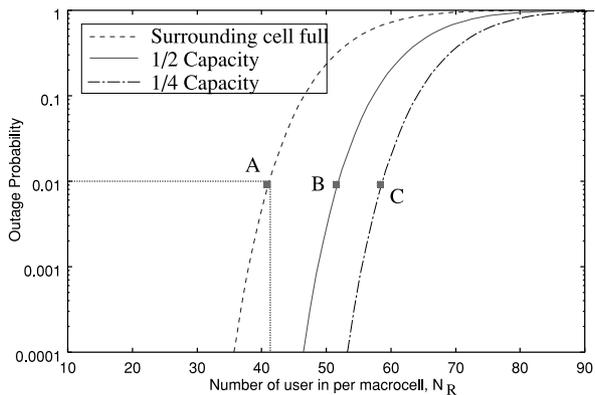
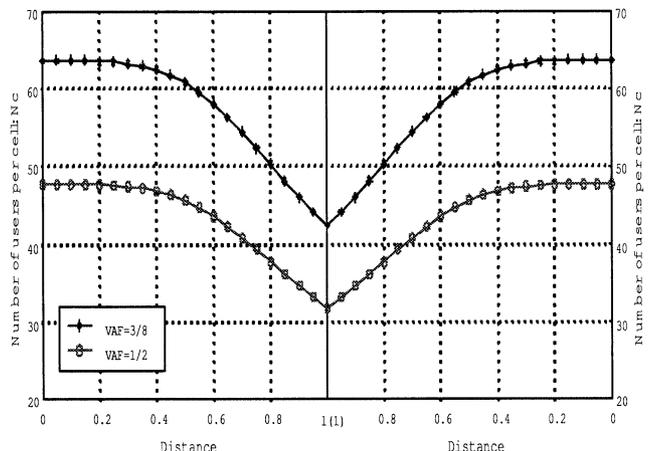


Fig. 6 Outage probability of macrocell with various loads of surrounding cells and VAF $\theta=3/8$.

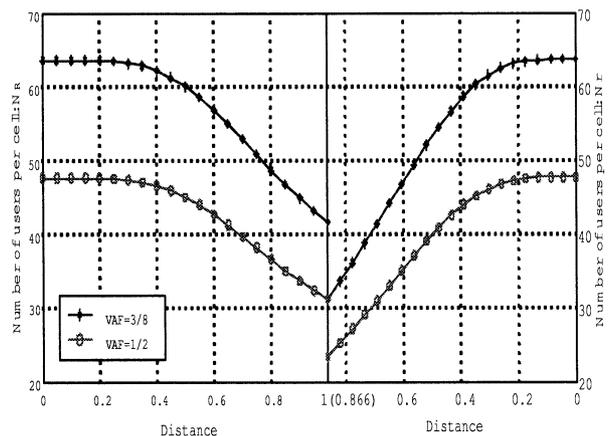
formance of macrocell is better than that of microcell because of the larger transmission power for macrocell users that degrade ISR of macrocell. On the other hand, the higher user density distribution in three micro cell areas that generate much more interference. According to the definition of system capacity, the system capacity will be obtained from Figs. 5 and 6. From the numerical results, this conclusion can be presented also from Table 1 that shows $E[I/S]$ of macrocell are smaller and its capacity is higher than that of microcell.

B. System Capacity

In the same way we have also calculated the system capacity of microcell and macrocell in a different distance between mobile users and the base station respectively. The results are plotted in Fig. 7. Figure 7(a) shows the system capacities of two adjacent cells in a DS-CDMA cellular system with uniform cell sizes. In contrast, Fig. 7(b) shows the system capacities of a microcell and its adjacent macrocell in a DS-CDMA cellular system with mixed cell sizes. One can see the effects on the system capacity of individual cells when the system is with the cell splitting into macrocell and microcell architecture. As an example, at the boundary the system capacity of a microcell is smaller than that



(a)



(b)

Fig. 7 System capacity of DS-CDMA cellular system in different conditions (a) uniform cells (b) mixed cells.

of macrocell. However, the nearer the distance between mobile users and a base station is, the closer the system capacities of macrocell and microcell are. Around the center of the base station both of them are almost equal.

The relationship between the system capacity versus the distance between mobile user and base station is better shown in three-dimensional(3-D) plots, as shown in Fig. 8, part(a) For VAF $\theta=3/8$ and part(b) for VAF $\theta=1/2$. One can observe the three-dimensional distribution of system capacities of macrocell and microcell in a straightforward view.

C. Discussion

Here, in this subsection we will discuss our numerical results of forward link and make a comparison between the forward link and reverse link presented in Ref. [5]. The system capacities of both forward link and reverse link are shown in Table 1, where we also show the averages of ISR of a microcell and a macrocell. From the results, we can see the contributions of each tier macrocells and microcells to ISR .

The results show that the system capacity of

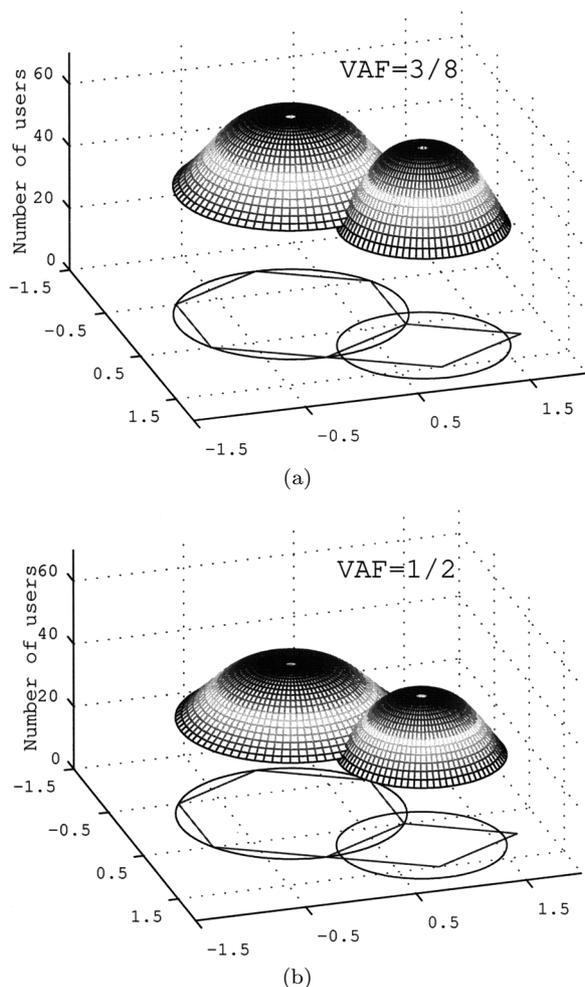


Fig. 8 Three-dimensional(3-D) distribution of the system capacity (a) VAF $\theta=3/8$ (b) VAF $\theta=1/2$.

Table 1 $E[I/S]$ and system capacities of microcell and macrocell. (VAF $\theta = 3/8$)

r/R	Link	Microcell	
		$E[I/S_r]$	Capacity
$\sqrt{3}/2$	Forward	$0.4447 N_r + 0.1890 N_R + 0.0504 N_C$	31
	Reverse[5]	$0.1221 N_r + 0.1147 N_R + 0.0495 N_C$	34

r/R	Link	Macrocell	
		$E[I/S_R]$	Capacity
$\sqrt{3}/2$	Forward	$0.0819 N_r + 0.4649 N_R + 0.0466 N_C$	41
	Reverse[5]	$0.1221 N_r + 0.0675 N_R + 0.1556 N_C$	29

macrocell is decreased by cell splits because of the increased interference resulted from the increased number of mobile users in the split cell area. Whether it is forward link or reverse link, system capacity can be increased by cell splits in any multiple access methods, such as FDMA, TDMA and also CDMA cellular system. From Fig. 7 and Table 1, considering the boundary situation and when r/R is $\sqrt{3}/2$, the system capacity of forward link in the split cell area is undoubtedly increased from 42 channels to $31 \times 3 = 93$ channels. From

the results of Ref. [5], the system capacity of reverse link in the split cell area is increased from 35 channels to $34 \times 3 = 102$ channels. The capacity increase is obtained at the expense of the capacity decrease at the macrocells surrounding the split cells. The capacity will decrease one user in every surrounding macrocell for forward link and two users for reverse link [5].

In order to understand the cell splits and set our results of forward link against that of Ref. [5], the cell split gain (CSG) in the system capacity is defined and represented as [5]

$$CSG = \frac{K_r \times N_r + K_R \times N_R}{K_C \times N_C} \tag{37}$$

where K_R is the number of first tiered macrocells surrounding three microcells and K_r is the number of these microcells. In particular, K_R and K_r are six and three, respectively. K_C is the number of uniform macrocells before cell splits.

Since the system capacity of forward link per cell is lower-limited by its value at the boundary, it will be investigated at boundary situation. Hence, from Eq. (37), the numerical results of CSG for the forward link and reverse link are

$$CSG = \begin{cases} 1.15 & \text{for forward link} \\ 1.12 & \text{for reverse link[5]} \end{cases} \tag{38}$$

6. Conclusions

The system capacity of forward link in a DS-CDMA cellular system with cell splitting into macrocell and microcell architecture has been analyzed. It has been found as follows. At the boundary situation, the system capacity of microcell is much smaller than that of macrocell. The nearer the distance between mobile users and base stations is, the closer the both of them are. At the center of the cell they are almost equal. The system capacity in the split cell areas increases as much as expected. This can be of significant importance to cope with growing demands in the mobile communication in densely populated areas. On the other hand, one can see the cell split gain, CSG of forward link is better than that of reverse link by contrastive study.

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