멀티미디어 서비스를 위한 스펙트럼 중첩 매크로/마이크로 셀룰러 CDMA 시스템의 역방향 링크 특성

(Reverse Link Characterization of a Spectrally Overlaid Macro/Micro Cellular CDMA System Supporting Multimedia Traffic)

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ABSTRACT

The reverse link of a spectrally overlaid macrocell/microcell cellular CDMA system supporting multimedia traffic is characterized in terms of the required signal power, interference, and capacity. Several narrowband subsystems are overlaid with a wideband subsystem in macrocells, while a single wideband subsystem is operated in a microcell with the same spectrum as the macrocell wideband subsystem. Using a typical propagation model the reverse link signal power and interference are characterized as the relative user signal power and the cross-tier interference factors between the macrocell and the microcell. The reverse link capacity of the overlay system is then analyzed. Analytical results show that the dominant parameters affecting the system performance are the spectral overlay ratio and the distance between the microcell and macrocell base stations. In particular, when the distance equals a half of macrocell radius, optimum performance can be achieved by minimizing the cross-tier interference factors. These results can be applied to CDMA multimedia network planning in heavily populated traffic areas.

Key words : *CDMA overlay, Multimedia traffic, Signal power, Interference, Capacity.*

I. Introduction

Flexible utilization of available radio spectra is an important issue since the radio spectra are limited resources. Furthermore, an increasing demand of future wireless multimedia services will require capacity enhancement of wireless communication systems.

Several techniques have been studied for enhancing the capacity of CDMA systems, including CDMA overlay systems with an existing TDMA system. Macrocell and microcell cellular systems with CDMA and TDMA overlays were studied in terms of capacity and interference characteristics[1]. In CDMA cellular networks, a microcell technique was widely investigated for cell boundary balancing and overlay-underlay cell clustering[2].

Spectrally overlaid CDMA systems have been the focus of recent research efforts in order to enhance the flexibility of spectrum utilization. A macrocell/microcell cellular CDMA system was studied in terms of the link capacity of the system[3], and an antenna

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tilt scheme was also proposed to increase the capacity of the CDMA system with overlaying a microcell on macrocell systems[4]. However, these previous studies considered only a single band macrocell/ microcell system supporting only a single type of traffic. The capacity and user signal power of single-code and multi-code CDMA overlay systems was studied[5, 6].

In this paper, we are concerned with the requiredsignal power, interference, and capacity of a spectrally overlaid macrocell and microcell cellular CDMA system supporting multimedia traffic. Multiple narrowband CDMA subsystems are spectrally overlaid with a wideband CDMA subsystem in macrocells, while asingle wideband CDMA subsystem is operated in the microcell within a reference macrocell. This overlay system can enhance the flexibility of the spectrum utilization and can accommodate rapidly growing traffic demands, including heavily populated areas called hot spots and shadowed regions.

The rest of this paper is organized as follows: In Section II a CDMA overlay system with a propagation model is described. Section III analyzes the required signal power and interference of the reverse link in termsof the relative user signal power and the cross-tier interference factors between a microcell and macrocells according to various system parameters. The reverse link capacity of the CDMA overlay system is analyzed in Section IV. Finally, Section V concludes this study.

Ⅱ. System Model

We consider a CDMA overlay system shown in Fig. 1. The system consists of multiple macrocells and one microcell located at a reference macrocell. In the macrocells several narrowband subsystems, where all narrowband subsystems are mutually exclusive, are spectrally overlaid on a wideband subsystem. Thus, no inter-narrowband interference exits. On the other hand, the microcell has a single wideband subsystem with the same spectrum as the wideband subsystem allocated to the macrocells.

The spreading bandwidth ratio of wideband subsystem to narrowband subsystem is defined as $W_w / W_n \equiv \varepsilon$. We consider the spectral overlay ratio of the narrowband to wideband subsystems, ζ, defined as $\zeta \equiv f/\varepsilon$ where f is the number of narrowband CDMA allocations overlaid with a wideband CDMA spectrum.

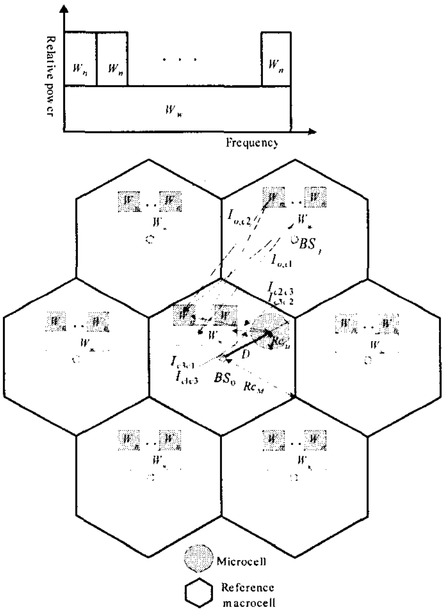

Fig.1 A spectrally overlaid macro/micro cellular CDMA system.

The system model and the associated assumptions used in this paper are summarized as follows:

1) The macrocell is assumed to be hexagonal with radius R_{c_M} and the single microcell is assumed to be circular with radius R_{c_μ} .

2) The microcell base station (BS) is located at a distance D from a reference macrocell BS.

3) Users are uniformly distributed in the microcell and macrocells.

4) All BSs of the subsystems are located at the center of each cell. The subsystems with different spreading bandwidths in macrocells are managed by the same BS.

5) Reverse link signal power of each CDMA subsystem is perfectly controlled by its home base station.

6) Propagation attenuation is modeled as the product of the fourth power of distance and a log-normal component representing shadowing losses, which is generally adopted in mobile radio propagation models[7].

Ⅲ. Signal Power and Interference

The reverse link of the overlay system is characterized in terms of the required user signal power and interference. The user signal power received from the reverse link is proportional to the user transmission power and is also required to maintain an acceptable link quality. Furthermore, macrocell and microcell users utilize different spreading bandwidths. Thus, they require different received signal power.

In a perfect power controlled CDMA system the bit energy-to-interference density ratio E_b/N_t received at a base station is maintained at a constant value. In the CDMA overlay system supporting Z types of traffic, the received $(E_b/N_t)_{q,c}$ of the q-th traffic type can be expressed as $(P_{q,c}/R_q)/[(P_{r,c}-P_{q,c})/W_c]$, where $R_q\ (q=1,2,\ldots,Z)$ is the information bit rate, $P_{q,c}$ is the received signal power, $P_{r,c}$ is the total power received at a base station of the overlaid subsystems, and the subscript c denotes the overlaid subsystems defined as

$$c=\begin{cases} c_1=(w,\ M);\ \textit{wideband macrocell} \\ c_2=(n,\ M);\ \textit{narrowband macrocell} \\ c_3=(n,\ \mu);\ \textit{wideband microcell} \end{cases}$$

Referring to [9], the relative signal power $\beta_{q,c}$ of the q-th traffic type and the first traffic type in the overlay system can be represented as

$$\beta_{q,c}\equiv\frac{P_{q,c}}{P_{1,c}}=\frac{\gamma_{q,c}(G_{1,c}+\gamma_{1,c})}{\gamma_{1,c}(G_{q,c}+\gamma_{q,c})} \quad (1)$$

where $G_{q,c}(=W_c/R_q)$ is the processing gain of the q-th traffic type, and $\gamma_{q,c}$ is the E_b/N_t required for maintaining a given acceptable link quality in the overlay system. The relative signal power $\beta_{q,c}$ is a constant for the q-th type of traffic.

To simplify our analysis, we here assume that: i) the wideband macrocells support voice and data traffic, ii) the narrowband macrocells accommodate only voice traffic, and iii) the microcell supports data traffic, respectively. Then, we can specify the condition to guarantee the quality of voice users by substituting the data user signal power $P_{d,c1}=\beta_{d,c1}P_{v,c1}$. Hereafter, the superscripts (or subscripts), M, , n, w, v, and d will be used to denote the macrocell, the microcell, the narrowband, and the wideband, voice and data, respectively.

A. Relative User Signal Power

Macrocell and microcell users utilize different spreading bandwidths, and thus, they require different signal power level to maintain their acceptable link qualities in the overlay system. To investigate the effect of the spreading bandwidth, the spectral overlay ratio, and log-normal shadow fading on the received user signal power, we examine the relative signal power required for the narrowband macrocell, wideband macrocell, and wideband microcell users, respectively.

Consider K users transmit in the microcell and macrocells. Then, the relative signal power of narrowband macrocell and wideband microcell users $P_{v,c2}/P_{d,c3}$ can be obtained as

$$\frac{P_{v,c2}}{P_{d,c3}} \equiv \beta_{c3}^{c2} = \frac{1 - \frac{K_{d,c3}}{K_{d,0}^{c3}}}{\left(\frac{\gamma_{d,c3}}{\gamma_{v,c2}}\right)\left[\frac{\psi_{c2c3}K_{v,c2}}{(1+\psi_{c2})K_{v,0}^{c2}} + \left\{\frac{\psi_{c1c3}K_{c1}}{(1+\psi_{c1})K_{v,0}^{c1}}\right\}\left\{1 + \frac{(\varsigma - 1)K_{v,c2}}{K_{v,0}^{c2}}\right\}\right]} \quad (2)$$

where $K_{c1} = K_{v,c1} + (\alpha_d/\alpha_v) K_{d,c1}\,\beta_{d,c1}$ and $\psi_{c3c1} = \psi_{c3c2}$, which will be discussed in Section III-B. $K_{v,0}^{c1} \equiv G_{v,w}/\{\gamma_{v,c1}\alpha_v(1+\psi_{c1})\}$ is the maximum number of voice users supportable in the wideband macrocell lacking narrowband macrocell and wideband microcell users. $K_{v,0}^{c2} \equiv G_{v,n}/\{\gamma_{v,c2}\alpha_v(1+\psi_{c2})\}$ is the maximum number of users that can be accommodated in the narrowband macrocell with no wideband macrocell and microcell users, and $K_{d,0}^{c3} \equiv G_{d,w}/\alpha_d\gamma_{d,c3}$ is the maximum number of users in the wideband microcell with no wideband and narrowband macrocell users.

In a similar way, the relative signal power of wideband macrocell and narrowband macrocell users $P_{v,c1}/P_{v,c2}$ is obtained as follows:

$$\frac{P_{v,c1}}{P_{v,c2}} \equiv \beta_{c2}^{c1} = \frac{\gamma_{v,c1}}{\gamma_{v,c2}}\left\{1 + \frac{(\varsigma - 1)K_{v,c2}}{K_{v,0}^{c2}}\right\} \quad (3)$$

Multiplying Eq. (2) by Eq. (3) yields the relative signal power of wideband macrocell and microcell users $P_{v,c1}/P_{d,c3}$.

B. Reverse Link Interference Analysis

As shown in Fig. 1, the total interference received at the respective macrocell and microcell base station consists of two types of interference: i) same-tier interference within the microcell and macrocells and ii) cross-tier interference between the microcell and macrocell. The same-tier interference consists of: i) the inner cell interference caused from the respective wideband and narrowband macrocells, $I_{in,c1}$ and $I_{in,c2}$, ii) the respective outer cell interference caused from the wideband and narrowband macrocells, $I_{o,c1}$ and $I_{o,c2}$, and iii) the interference within the microcell I_{c3}. The cross-tier interference is the interference from the wideband macrocells to the microcell I_{c1c3}, the interference from the narrowband macrocells to the microcell I_{c2c3}, and the interference from the microcell to the reference narrowband and wideband macrocells, I_{c3c2} and I_{c3c1}.

The same-tier interference in macrocells is characterized by the two interference factors, ψ_{c1} and ψ_{c2}[8]. Herein, we characterize the cross-tier interference as both the microcell-to-macrocell interference factors, ψ_{c3c1} and ψ_{c3c2}, and the macrocell-to-microcell interference factors, ψ_{c1c3} and ψ_{c2c3}.

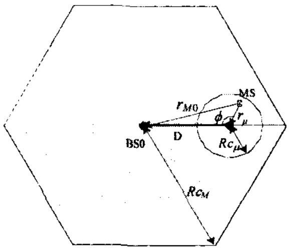

Fig. 2 The interference received at the reference macrocell BS from a microcell.

1) Microcell-to-Macrocell Interference

Consider a mobile user located in the microcell at a distance of r_μ from the microcell BS and a distance of

$$r_{M0} = \sqrt{D^2 + r_\mu^2 - 2Dr_\mu \cos\phi} \quad (5)$$

from the reference macrocell BS0, as shown in Fig. 2. In (5), D is the distance between the microcell BS and the reference macrocell *BS0*. We also consider a radio propagation channel with a fourth path-loss exponent and a log-normal random variable λ with a standard deviation of σ .

Then the interference received at the reference macrocell $BS0$ caused by the microcell user I_{c3c2} is obtained as

$$I_{c3c2} = \left(\frac{r_\mu}{r_{M0}}\right)^4 10^{(\lambda_M - \lambda_\mu)/10} P_{d,c3}$$
$$= \left(\frac{r_\mu}{r_{M0}}\right)^4 10^{\chi/10} P_{d,c3}, \quad (6)$$

where $\chi = \lambda_M - \lambda_\mu$ is a Gaussian random variable having zero mean and a standard deviation of $\sqrt{2}\sigma$, as λ_μ and λ_M are two independent fading variables. The interference received at the reference macrocell depends on the mobile user location in the microcell and the shadowing conditions. Accordingly, the total average interference to the narrowband macrocell $BS0$ caused by the microcell users, I^{cross}_{c3c2}, can be obtained by averaging I_{c3c2} over all possible points r_μ in the microcell.

$$I^{cross}_{c3c2} = E[I_{c3c2}]$$
$$= \int_0^{2\pi}\int_0^{Rc_\mu} \frac{K_{d,c3}}{\pi Rc_\mu^2}\left(\frac{r_\mu}{r_{M0}}\right)^4 E\left[\Phi\left(\chi, \frac{r_\mu}{r_{M0}}\right)10^{\chi/10}\right] P_{d,c3} r_\mu dr_\mu d\phi \quad (7)$$

where $\Phi\left(\chi, \frac{r_\mu}{r_{M0}}\right) = \begin{cases} 1, & \text{for} \left(\frac{r_\mu}{r_{M0}}\right)^4 10^{\chi/10} \le 1 \\ 0, & \text{otherwise} \end{cases}$ This relation accounts for the mobile users communicating with the microcell BS that offers the least signal attenuation under the path-loss and shadowing conditions. The expectation of (7) can be shown to be

$$E\left[\Phi\left(\chi, \frac{r_\mu}{r_{M0}}\right)10^{\chi/10}\right] = \exp\left(\frac{\sigma \ln 10}{10}\right)^2 \left\{1 - Q\left[\frac{40\log_{10}(r_{M0}/r_\mu)}{\sqrt{2\sigma^2}} - \frac{\sqrt{2\sigma^2}\ln 10}{10}\right]\right\} \quad (8)$$

where $Q \equiv \frac{1}{\sqrt{(2\pi)}}\int_{-\infty}^{\infty} e^{-y^2/2} dy$. Hence, the interference factor of microcell-to-narrowband macrocell ψ_{c3c2} can be obtained by normalizing I^{cross}_{c3c2} to $K_{d,c3} P_{d,c3}$.

$$\psi_{c3c2} = \int_0^{2\pi}\int_0^{Rc_\mu} \frac{1}{\pi Rc_\mu^2}\left(\frac{r_\mu}{r_{M0}}\right)^4 E\left[\Phi\left(\chi, \frac{r_\mu}{r_{M0}}\right)10^{\chi/10}\right] r_\mu dr_\mu d\phi \quad (9)$$

In a similar way, the interference factor of microcell-to-wideband macrocell ψ_{c3c1} can be found to be $\psi_{c3c1} = \psi_{c3c2}$, which is obtained by normalizing the average interference received at the reference wideband macrocell *BS0* caused by the microcell users to $K_{d,c3} P_{d,c3}$.

2) Macrocell-to-Microcell Interference

The cross-tier interference experienced at the microcell is originated from a reference macrocell as well as neighboring macrocells. First, we investigate the interference experienced at the microcell due to the reference macrocell. Let us consider a mobile user located in the reference narrowband macrocell at a distance of r_{M0} from the macrocell $BS0$ and a distance of

$$r_{\mu 0} = \sqrt{D^2 + r_{M0}^2 - 2Dr_{M_0}\cos(\omega)} \quad (10)$$

from the microcell BS.

As shown in Fig. 3, we here consider the first-tier (6 macrocells) and the second-tier (12 macrocells) interference.

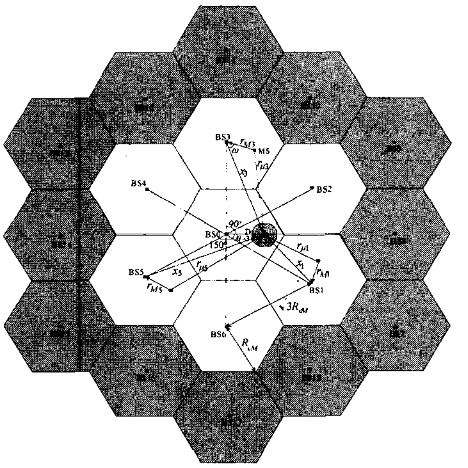

Fig. 3 The interference received at a microcell BS from neighboring macrocells.

The interference experienced at the microcell BS_{μ} caused by the reference macrocell and the other neighboring macrocell users is expressed as

$$(I_{c2c3})_j = \left(\frac{r_{Mj}}{r_{\mu j}}\right)^4 10^{(\lambda_{\mu j}-\lambda_{Mj})/10} P_{v,c2} \quad , \qquad (11)$$

where $j=0,1,2,\ldots,J-1$. Approximating the hexagonal macrocells by a circular cell of radius R_{c_M}, the total average interference experienced at the microcell BS that is caused by the narrowband macrocell users, I_{c2c3}^{cross} can be obtained as

$$I_{c2c3}^{cross} = E[(I_{c2c3})_j]$$
$$= \sum_{j=0}^{J-1}\int_0^{2\pi}\int_0^{R_{c_M}} \frac{K_{v,c2}}{\pi R_{c_M}^2}\left(\frac{r_{Mj}}{r_{\mu j}}\right)^4 E\left[\Phi_j\left(\chi_j,\frac{r_{Mj}}{r_{\mu j}}\right)10^{\chi_j/10}\right] P_{v,c2} r_{Mj} dr_{Mj} d\omega \qquad (12)$$

where $\chi_j = \lambda_{Mj} - \lambda_{\mu j}$ and

$$\Phi_j\left(\chi_j,\frac{r_{Mj}}{r_{\mu j}}\right) = \begin{cases} 1, & \text{for} \left(\frac{r_{Mj}}{r_{\mu j}}\right)^4 10^{-\chi_j/10} \le 1 \\ 0, & \text{otherwise} \end{cases} .$$

Using (12), the interference factor of narrowband macrocell-to-microcell ψ_{c2c3} can be obtained as

$$\psi_{c2c3} = \frac{I_{c2c3}^{cross}}{K_{v,c2}P_{v,c2}}$$
$$= \sum_{j=0}^{J-1}\int_0^{2\pi}\int_0^{R_{cM}} \frac{1}{\pi R_{cM^2}}\left(\frac{r_{Mj}}{r_{\mu j}}\right)^4 \exp\left(\frac{\sigma \ln 10}{10}\right)^2 x$$
$$Q\left[\frac{-40\log_{10}(r_{\mu j}/r_{Mj})}{\sqrt{2\sigma^2}} + \frac{\sqrt{2\sigma^2}\ln 10}{10}\right] r_{Mj} d_{r_{Mj}} dw$$

where $r_{\mu j} = \sqrt{x_j^2 + r_{Mj}^2 - 2x_j r_{Mj}\cos\omega} \quad \text{for} \; 0 \le j \le 18$

$$x_j = \begin{cases} D & \text{for}\; j=0 \\ \sqrt{(\sqrt{3}R_{C_M})^2 + D^2 - 2\sqrt{3}R_{C_M}D\cos\theta_j} & \text{for}\; j=1,2,3,4,5,6 \\ \sqrt{(2\sqrt{3}R_{C_M})^2 + D^2 - 4\sqrt{3}R_{C_M}D\cos\theta_j} & \text{for}\; j=7,9,11,13,15,17 \\ \sqrt{(3R_{C_M})^2 + D^2 - 6R_{C_M}D\cos\theta_j} & \text{for}\; j=8,10,12,14,16,18 \end{cases}$$

$$\cos\theta_j = \begin{cases} 1 & \text{for}\; j=8 \\ \sqrt{3}/2 & \text{for}\; j=1,2,7,9 \\ 1/2 & \text{for}\; j=10,18 \\ 0 & \text{for}\; j=3,6,11,17 \\ -1/2 & \text{for}\; j=12,16 \\ -\sqrt{3}/2 & \text{for}\; j=4,5,13,15 \\ -1 & \text{for}\; j=14 \end{cases}$$

Similarly, the interference factor of wideband macrocell-to-microcell, ψ_{c1c3}, can be obtained by normalizing the average microcell interference caused by the wideband macrocell users to $K_{c1}P_{v,c1}$, and thus, the interference factors ψ_{c1c3} equals $\varsigma\psi_{c2c3}$.

C. Numerical Results and Discussions

In order to evaluate the relative user signal power and the cross-tier interference factors in the overlay system, the system parameters shown in Table I are considered. The microcell radius is normalized to the macrocell radius, which is given by $R_{c_M}=1$. The parameters $K_{v,0}^{c1}$, $K_{v,0}^{c2}$ and $K_{d,0}^{c3}$ are set at 619, 154 and 95, respectively. The relative signal power $\beta_{d,c1}$ of data and voice users in the wideband macrocell is obtained as 9.8. Thus, the data users require $\beta_{d,c1}$ times more power than do voice users in wideband macrocells and the number of voice users $K_{v,c1}$ effectively corresponds to 9.8 times $K_{d,c1}$ in terms of the number of users. We here assume that the numbers of voice users assigned to the overlaid subsystems c_2 and c_3 are given by $K_{v,c2}=61$ and $K_{d,c3}=38$, respectively. In addition, the number of voice users $K_{v,c1}$ is assumed to be 149 in each wideband macrocell c_1 when the number of data users $K_{d,c1}$ allocated to the subsystem c_1 is assumed to be 10. A wider bandwidth may resolve more multipaths than a narrower bandwidth in CDMA systems, but we assume

$\gamma_{v,c1}=\gamma_{v,c2}$ for analysis of the effect of the other system parameters on the signal power and interference in the overlay system.

Table I. List of System Parameters

Bandwidth of wideband subsystem, W_w		19.20 MHz
Bandwidth of narrowband subsystem, W_n		4.80 MHz
Information bit rate, R	voice, R_v	8 $kbps$
	data, R_d	64 $kbps$
Require E_b/N_o, γ	voice, $\gamma_{v,c1}=\gamma_{v,c2}$	7 dB
	data, $\gamma_{d,c1}=\gamma_{d,c2}$	8 dB
Activity factor, α	voice, α_v	0.5
	data, α_d	0.5
Spectral overlay ratio, ς		0.25, 0.5, 1.0
Same-tier interference factors ψ_{c1}, ψ_{c2}		0.55
Relative cell radius, Rc_μ/Rc_M		0.1, 0.2, 0.3
A standard deviation of shadowing loss, σ		6 dB, 7 dB, 8 dB

Fig. 4 shows the interference factor of microcell-to-narrowband macrocell in the overlay system. The interference experienced at the reference macrocell base station caused by a microcell decreases as the distance between the macrocell BS and microcell BS increases. In particular, the interference is significantly reduced when the distance D is greater than $0.5Rc_M$. Furthermore, the microcell size also affects the cross-tier interference in the overlay system such that, as the difference of the cell radius between microcell and macrocell increases, the interference factor is reduced.

However, the interference factor of microcell-to-narrowband macrocell increases as the effect of shadowing in both the microcell and macrocell increases. When the relative cell radius $R_{c\mu}/R_{cM}$ is small, the increase of shadowing does not highly affect the interference factor ψ_{c3c2}.

On the other hand, with a large value of $R_{c\mu}/R_{cM}$, the effect of shadowing on the interference factor increases significantly. For example, when $R_{c\mu}/R_{cM}=0.3$, 1 dB increase of the shadowing results in about two-fold increase of the interference factor. In a heavy shadowing case (e.g., $\sigma=8dB$ and $D=0.4$), the interference factor ψ_{c3c2} is given by 0.093 which is a relatively small value when compared to the same-tier interference factor ψ_{c1}, ψ_{c2} (assumed as 0.55).

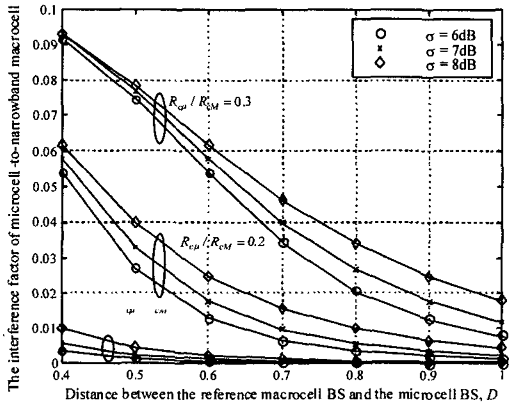

Fig. 4 The interference factor of microcell-to-narrowband macrocell ψ_{c3c2} according to D, σ and $R_{c\mu}/R_{cM}$ ($R_{cM}=1$).

Fig. 5 shows the interference factor of narrowband macrocell-to-microcell. The interference received at the microcell BS caused by the narrowband macrocells slightly increases as the shadowing effect in the microcell and macrocells increases. The effect of shadowing loss on the cross-tier interference factor ψ_{c2c3} is smaller when compared to the same effect on the cross-tier interference factor ψ_{c3c2}. Unlike the value of distance D affecting the interference factor ψ_{c3c2}, the interference received at the microcell also increases as the distance between the microcell BS and macrocell BS increases. With a greater distance from the reference macrocell *BS*, the effect of more interference from the neighboring macrocells for the microcell BS is *greater than* the effect of decreased interference from the other remote macrocells.

A dominant parameter affecting the two interference factors is the distance between the reference macrocell BS and the microcell BS.

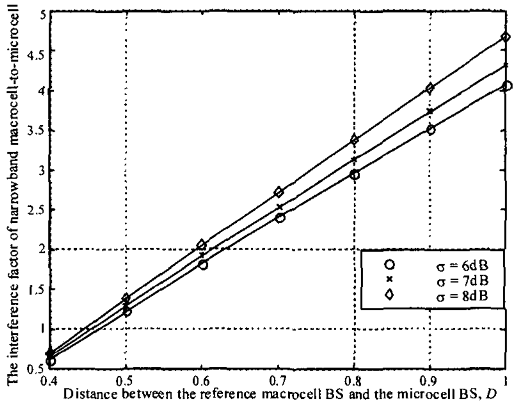

Fig. 5 The interference factor of microcell-to-narrowband macrocell ψ_{c2c3} according to D and σ.

From Figs. 5 and 6, for a relative cell radius $R_{c\mu}/R_{cM}=0.3$ and a standard deviation of shadowing loss $\sigma=8\,dB$, the optimum distance D is approximately 0.5, which minimizes both of the interference factors in the CDMA overlay system.

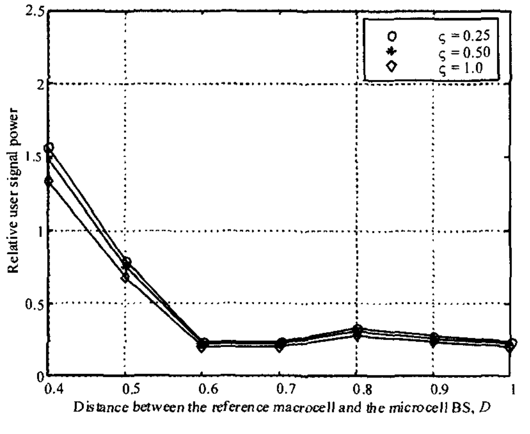

Fig. 6 The relative user signal power $P_{v,c2}/P_{d,c3}$ according to the distance D and the spectral overlay ratio ($\sigma=8\,dB$, $Rc_M=1$, $K_{v,c2}=61$, $K_{d,c3}=38$, $K_{v,c1}=149$, and $K_{d,c1}=10$).

Fig. 6 shows the relative signal power of narrowband macrocell and microcell users $P_{v,c2}/P_{d,c3}$, which is the required signal power of macrocell users relative to the required signal power of microcell users. With a small distance D, the narrowband macrocell users require more power. For example, $P_{v,c2}/P_{d,c3}\approx 1.6$ when $D=0.4$ and $\zeta=0.25$. However, when D is greater than $0.5R_{cM}$, microcell data users require more power than the narrowband macrocell users. Furthermore, the required signal power difference between narrowband macrocell and wideband microcell users slightly decreases with a large spectral overlay ratio.

Ⅳ. Reverse Link Capacity

The link capacity of a CDMA system with only a single traffic type is generally defined as the maximum number of active users maintaining their acceptable link quality inthe system. However, the CDMA overlay system supports various types of traffic with different data rates, and the traffic types require different power level. Hence, we here investigate the capacity of the overlay system supporting Z types of traffic in terms of *the equivalent total throughput* $(T_e)_c$, which is defined as the total aggregated data rate achievable in the narrowband and wideband macrocells and the microcell.

$$(T_e)_c = R_1 \sum_{c} \sum_{q=1}^{Z} \alpha_q \beta_{q,c} K_{q,c} \quad (14)$$

where R_1 is the information bit rate of the first type of traffic, and c represents the subsystems of the CDMA overlay system. As described in the previous section, for simplicity, we consider that voice and data in the wideband macrocells, voice only in the narrowband macrocells, and data only in the microcell are supported, respectively.

A. Link Capacity Analysis

Considering the constraint of link quality in each subsystem, the maximum number of voice users supporting in the wideband macrocell can be expressed as

$$K_{v,c1} \le K_{v,0}^{c1}\left[1-\left\{\frac{\gamma_{v,c1}}{\gamma_{v,c2}}\frac{\varsigma K_{v,c2}}{\beta_{c2}^{c1}K_{v,0}^{c2}}+\frac{\gamma_{v,c1}}{\gamma_{d,c3}}\frac{\psi_{c3c1}K_{d,c3}}{\beta_{c3}^{c1}K_{d,0}^{c3}}\right\}\right]-\left(\frac{\alpha_d}{\alpha_v}\beta_{d,c1}K_{d,c1}\right) \quad (15)$$

where $K_{v,0}^{c1}$, $K_{v,0}^{c2}$ and $K_{v,0}^{c3}$ are defined in Section III. In a similar way, dividing $P_{v,c2}$ and $P_{v,c3}$ into (4) and (5), respectively, the maximum number of voice users that can be accommodated in the respective narrowband macrocell and the wideband microcell can be obtained.

$$K_{v,c2} \le K_{v,0}^{c2}\left[1-\left\{\frac{\gamma_{v,c2}}{\gamma_{d,c3}}\frac{\psi_{c3c2}K_{d,c3}}{\beta_{c3}^{c2}K_{d,0}^{c3}}+\frac{\gamma_{v,c2}}{\gamma_{v,c1}}\frac{\beta_{c2}^{c1}K_{t,c1}}{\alpha_v K_{v,0}^{c1}}\right\}\right] \quad (16)$$

$$K_{d,c3} \le K_{d,0}^{c3}\left[1-\left\{\frac{\gamma_{d,c3}}{\gamma_{v,c2}}\frac{\psi_{c2c3}}{1+\psi_{c2}}\frac{\beta_{c3}^{c2}K_{v,c2}}{K_{v,0}^{c2}}+\frac{\gamma_{d,c3}}{\gamma_{v,c1}}\frac{\psi_{c1c3}}{1+\psi_{c1}}\frac{\beta_{c3}^{c1}K_{t,c1}}{\alpha_v K_{v,0}^{c1}}\right\}\right] \quad (17)$$

where $K_{t,c1} \equiv \alpha_v K_{v,c1} + \alpha_d K_{d,c1} \beta_{d,c1}$.

The relative signal power β_{c3}^{c2} and β_{c3}^{c1} are functions of $K_{v,c2}$, $K_{d,c3}$ and K_{c1}. However, β_{c2}^{c1} is not a function of K_{c1}. Thus, eliminating β_{c3}^{c2} and β_{c3}^{c1} in (15), (16), and (17) yields the maximum number of users K_{c1} accommodated in the wideband macrocell as functions of the spectral overlay ratio, the cross-tier interference factor, and the number of voice users allocated to the wideband microcell and narrowband macrocells.

$$K_{c1} = \frac{-Y_b + \sqrt{Y_b^{\,2} - 4Y_aY_c}}{2Y_a}, \quad (18)$$

$$Y_a = \left\{\frac{(K_{v,0}^{c2}+(\varsigma-1)K_{v,c2})}{K_{d,0}^{c3}K_{v,o}^{c2}K_{v,0}^{c1}}\right\}\left\{\frac{(K_{d,0}^{c3}-K_{d,c3})}{K_{v,0}^{c1}}+\frac{\psi_{c3c1}\psi_{c1c3}K_{d,c3}}{(1+\psi_{c1})K_{v,0}^{c1}}\right\}$$

$$Y_b = -\left\{\frac{2(K_{d,0}^{c3}-K_{d,c3})(K_{v,0}^{c2}-K_{v,c2})}{K_{d,0}^{c3}K_{v,0}^{c2}K_{v,0}^{c1}}+\frac{\psi_{c3c1}\psi_{c1c3}K_{d,c3}(K_{v,0}^{c2}-2K_{v,c2})}{(1+\psi_{c1})K_{d,0}^{c3}K_{v,0}^{c2}K_{v,0}^{c1}}\right\}$$

$$Y_c = \frac{(K_{v,0}^{c2}-K_{v,c2})}{(K_{v,0}^{c2}+(\varsigma-1)K_{v,c2})}\left\{\frac{\psi_{c3c2}\psi_{c2c3}K_{d,c3}K_{v,c2}}{(1+\psi_{c2})K_{d,0}^{c3}K_{v,0}^{c2}}\;\frac{(K_{d,0}^{c3}-K_{d,c3})(K_{v,0}^{c2}-K_{v,c2})}{K_{d,0}^{c3}K_{v,0}^{c2}}\right\}$$

Hence, the equivalent total throughput $(T_e)_{c1}$ achievable in the wideband macrocell is obtained as,

$$\begin{aligned}(T_e)_{c1} &= R_v(\alpha_v K_{v,c1} + \alpha_d \beta_{d,c1} K_{d,c1})\\ &= R_v \alpha_v K_{c1}\end{aligned} \quad (19)$$

From (18) and (19) we can observe the following: As the number of users allocated to the narrowband macrocell and the wideband microcell approaches zero, the equivalent throughput of the wideband macrocell approaches $R_v \alpha_v K_{v,0}^{c1}$. Whereas the $(T_e)_{c1}$ decreases to zero when the narrowband spectra are fully overlaid on the wideband spectrum in macrocells, i.e., $\zeta=1$, and the capacity of the narrowband macrocell is fully occupied, i.e., $K_{v,c2} = K_{v,0}^{c2}$.

B. Numerical Results and Discussions

The reverse link capacity of the overlay system is evaluated in terms of the equivalent total throughput achievable in the subsystems. The system parameters for the evaluation are the same as those used in Table I and Section III. We also assume that traffic load of the wideband microcell is 40 percent of the maximum data capacity $K_{d,0}^{c3}$ accommodated in non-overlay environments. That is, 38 data users are assigned to the microcell.

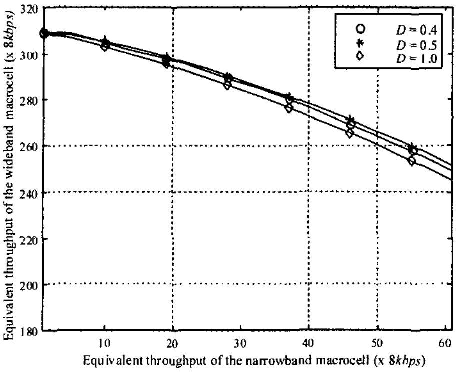

Fig. 7 The capacity of the wideband macrocell subsystem versus that of the narrowband macrocell subsystem($\sigma=8\,dB$, $R_{c\mu}/R_{cM}=0.2$ and $K_{d,c3}=38$)

Fig. 7 shows the wideband macrocell throughput versus the narrowband macrocell throughput for the different values of the distance D when the microcell load equals 40 %. With a distance of 0.5, the optimum performance can be achieved in terms of the equivalent throughput of the wideband macrocell. This is because the cross-tier interference factors between the microcell and macrocells are minimized. This result can be inferred from Figs. 5 and 6.

The capacity of the overlay system increases as the standard deviation of shadowing loss and the relative cell size $R_{c\mu}/R_{cM}$ decrease, which can be estimated from the results of the cross-tier interference analysis.The dominant parameters affecting the system performance are the spectral overlay ratio and the location of the microcell BS in the macrocell.

V. Conclusions

The reverse link of a spectrally overlaid macro/micro cellular CDMA system supporting multimedia traffic wascharacterized in terms of the required signal power, interference, and capacity in a typical propagation environment.The required signal power and interference were analyzed for the relative user signal power and the cross-tier interference factors between a wideband microcell and narrowband and wideband macrocells.

To evaluate the effect of various system parameters, we considered the spectral overlay ratio, a shadow fading, the relative cell radius of the microcell and macrocells,and the distance between a reference macrocell BS and a microcell BS, and so on. The dominant parameters affecting the system performance are the spectral overlay ratio and the distance. The optimum distance for minimization of the cross-tier interferencefactors and maximization of the link capacity is approximately a half of the macrocell radius. Therefore, it is critical to plan the location of a microcell BS within macrocells and to efficiently assign radio resources in spectrally overlaid macrocell/ microcell cellular CDMA systems.

In future wireless communication systems the forward link may be a more important restraint on system capacity than the reverse link. A forward link characterization with consideration of multipath fading environments is left for further study.

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