IEICE TRANS. COMMUN., VOL.E90–B, NO.4 APRIL 2007

PAPER

A DS-CDMA Cellular System Using Band Division and Channel Segregation Distributed Channel Allocation

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SUMMARY In DS-CDMA cellular communications systems, the single frequency reuse can be utilized. Since large other-cell interference is produced, the well known soft handover or site diversity must be used. If the single frequency reuse is not utilized to avoid the other-cell interference, we will face the frequency allocation problem, similar to FDMA systems. In this paper, a DS-CDMA cellular system using band division is proposed. The available wide frequency band is divided into several narrow frequency bands and the different frequency bands are allocated to adjacent cells so as to avoid the large other-cell interference. For the frequency allocation, the channel segregation distributed channel allocation (CS-DCA) algorithm is applied. The link capacity is evaluated by computer simulation.

key words: *channel assignment, channel segregation, DS-CDMA, link capacity*

1. Introduction

In frequency division multiple access (FDMA), the same frequency band is reused at the different cells in order to efficiently utilize the limited bandwidth [1]. However, we will face the frequency allocation problem. On the other hand, in direct sequence code division multiple access (DS-CDMA) [2], single frequency reuse is possible and much better spectrum efficiency is achieved, therefore DS-CDMA is adopted in the 3rd generation mobile communication systems [3]. In DS-CDMA, Rake combining is used to resolve the propagation channel into several paths for coherent combining to get the path diversity effect and to improve the transmission performance. Since large other-cell interference is produced, soft handover or site diversity must be used [2]. If available band is divided into several narrow frequency bands and the same band is not used at adjacent cells, large other-cell interference can be avoided, while no site diversity gain is obtained. However, we will face the channel allocation problem, similar to FDMA cellular systems [1]. There are two types of channel allocation: one is the fixed channel allocation (FCA) and the other is the dynamic channel allocation (DCA) [6]. Using FCA, predetermined fixed channels are allocated to each BS. FCA cannot adapt to changing traffic conditions and user distributions. On the other hand, using DCA, all channels are given to each BS and one of the channels is used if the channel meets the required quality. One efficient DCA solution is the channel segregation DCA (CS-DCA) [4] proposed for FDMA cellular system. In this paper, the CS-DCA is applied for the band division DS-CDMA cellular system. The objective of this paper is to evaluate, by the computer simulation, the DS-CDMA link capacity using band division and CS-DCA and to compare with DS-CDMA using the single frequency reuse and site diversity.

The remainder of this paper is organized as follows. Section 2 describes a DS-CDMA cellular system using band division and CS-DCA. Section 3 evaluates the link capacity by computer simulation. Section 4 gives some conclusions.

2. A DS-CDMA Cellular System Using Band Division and CS-DCA

A DS-CDMA cellular system using band division and CS-DCA is introduced. The CS-DCA algorithm is presented. When the measured signal-to-noise plus interference power ratio (SINR) is less than the required value, the channel allocation fails. For computer simulation of evaluating the link capacity, it is necessary to find the SINR expression. The theoretical expression of SINR is derived. We assume the log-normally distributed shadowing loss and Rayleigh fading.

2.1 Band Division

As shown in Fig. 1, the available wide frequency band is divided into K narrow frequency bands. The CS-DCA algorithm [4] is applied so as to allocate the different frequency bands to adjacent cells. As K increases, the other-cell interference can be reduced, thereby increasing the link capacity. However, as the channel bandwidth becomes narrower, the number L of resolvable paths becomes smaller. This leads to reducing the path diversity effect achievable with Rake combining and thus decreasing the link capacity. This indicates that the link capacity depends on K and L.

2.2 CS-DCA Algorithm

In CS-DCA, base station (BS) has channel priority table and equivalently learns the cell structure without requiring any propagation information in advance [4]. The frequency allocation is self-organized, resulting in the improved spectrum efficiency. Table 1 shows an example of the priority table, where $n(k)$ is the frequency band index having the k-th highest channel priority. In the priority table, the priority value

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Manuscript received June 16, 2005.
Manuscript revised February 9, 2006.

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DOI: 10.1093/ietcom/e90–b.4.904

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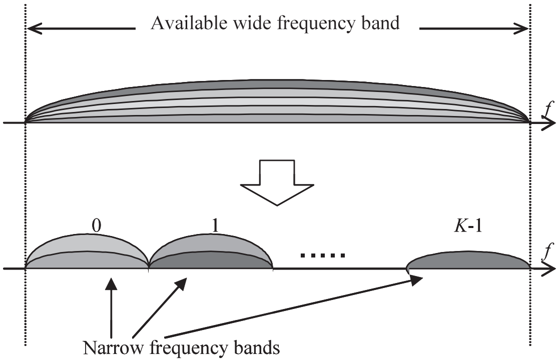


Fig. 1 Band division.

Table 1 An example of frequency band priority table.

k	$n(k)$	$P(n)$	$N(n)$
1	7	0.813	246
2	2	0. 574	87
3	1	0. 467	107
...	...	...	...
K	4	0.059	17

$P(n)$ and the number $N(n)$ of times the $n(k)$-th frequency band has been tested are listed, where $P(n)$ is defined as (the number of times the n-th frequency band has been successfully allocated)/$N(n)$. This paper considers the uplink capacity with the SNR based transmit power control and thus the received signal power at the BS is kept at the constant target value for all mobile stations (MSs). Therefore, the communication quality does not depend on the communicating MS location and the $P(n)$ does not depend on the communicating MS locations.

Figure 2 shows the flow chart of frequency allocation using CS-DCA algorithm, where ":=" denotes the substitution operation. If the BS receives the channel request message from an MS, the BS selects a frequency band having the highest priority and measures the SINR of the selected frequency band. If the SINR meets the quality requirement (or the required SINR), $P(n)$ is increased and the selected frequency band is allocated. Otherwise, the frequency band priority value is decreased. Then, the BS selects another frequency band having the next highest priority value for the SINR measurement and comparison. If the available frequency channel is not found, this call is blocked. Updating of the frequency band priority value is described below.

When the $n(k)$-th frequency band is successfully allocated, $P(n)$ and $N(n)$ are updated as [4]

$$\begin{cases} P(n) := [P(n) \cdot N(n) + 1]/[N(n) + 1] \\ N(n) := N(n) + 1 \end{cases}. \tag{1}$$

When the allocation of the $n(k)$-th frequency band fails, $P(n)$ and $N(n)$ are updated as

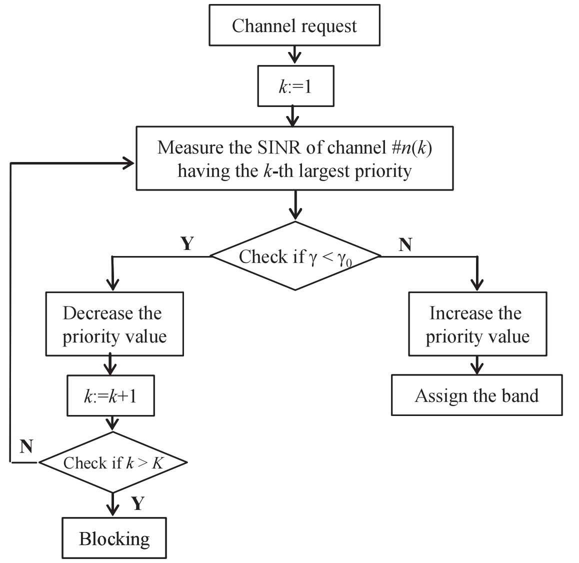


Fig. 2 Flow chart of frequency allocation using CS-DCA algorithm.

$$\begin{cases} P(n) := P(n) \cdot N(n)/[N(n) + 1] \\ N(n) := N(n) + 1 \end{cases}. \tag{2}$$

The probability that the frequency band is usable (i.e., the SINR of that frequency band is larger than the required value) is denoted as $q(n)$. After the frequency band priority value has been updated many times, the following relationship holds

$$P(n)=q(n)\cdot\frac{P(n)\cdot N(n)+1}{N(n)+1}+[1-q(n)]\cdot\frac{P(n)\cdot N(n)}{N(n)+1}. \tag{3}$$

From Eq. (3), we obtain $P(n) = q(n)$. This means that $P(n)$ approaches the probability of the $n(k)$-th frequency band being usable. Therefore, a frequency band having higher usable probability is selected more frequently.

2.3 SINR

The propagation channel can be characterized by the distance dependent path loss, log-normally distributed shadowing loss and fading [1]. An L-path fading with uniformly distributed power delay profile, QPSK data modulation and the SNR-based ideal transmit power control (TPC) are assumed. When the available band is divided into K narrow bands, the spreading factor SF_K is $SF_K=SF/K$ and the number L_{eq} of resolvable paths becomes $L_{eq} = L/K$. We assume ideal L_{eq}-finger maximal-ratio Rake combining.

The instantaneous SNR $(S/N)_{i,j}$ of the signal transmitted from the i-th MS and received at the j-th BS is given by [5]

$$(S/N)_{i,j} = (P_t/N)_i \cdot r_{i,j}^{-\alpha} \cdot 10^{-\eta_{i,j}/10} \cdot \sum_{l=0}^{L_{eq}-1} \left|\xi_{i,j}(l)\right|^2, \tag{4}$$

where $(P_t/N)_i$ represents the transmit power-to-noise power ratio of the i-th MS, $r_{i,j}$ represents the distance between the i-th MS and the j-th BS, α the path loss exponent, $\eta_{i,j}$ the log-normally distributed shadowing loss in dB, $\xi_{i,j}(l)$ the l-th path gain following the complex Gaussian distribution, and L_{eq} the number of resolvable paths. When K=1, the signal transmitted from the i-th MS is received by all BS's and a BS having the largest received instantaneous SNR is selected for the communication with the i-th MS and is represented by $j(i)$, i.e.,

$$j(i) = \arg\max_{j} \left\{ r_{i,j}^{-\alpha} \cdot 10^{-\eta_{i,j}/10} \cdot \sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j}(l) \right|^2 \right\}. \tag{5}$$

Note that the communicating BS (i.e., the $j(i)$-th BS) changes during a call. $(P_t/N)_i$ is omitted from Eq. (5), since $(P_t/N)_i$ has no effect on the selection of BS. On the other hand, when $K > 1$, each MS communicates with a BS that provides the largest *local average* SNR. Therefore, when $K > 1$, the Eq. (5) can be rewritten as

$$j(i) = \arg\max_{j} \left\{ r_{i,j}^{-\alpha} \cdot 10^{-\eta_{i,j}/10} \right\}. \tag{6}$$

Denoting the TPC target by $(S/N)_{target}$, $(P_t/N)_i$ is given by

$$\begin{aligned}(P_t/N)_i &= (S/N)_{target} \cdot r_{i,j(i)}^{\alpha} \cdot 10^{\eta_{i,j(i)}/10} \\ &\quad \cdot \left(\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j(i)}(l) \right|^2 \right)^{-1}.\end{aligned} \tag{7}$$

Without loss of generality, the 0-th MS communicating with the 0-th BS (i,e., i=0 and $j(i)$=0(0)) is considered as an MS of interest. The SINR γ after ideal Rake combining at the 0(0)-th BS is given by

$$\gamma = \frac{(S/N)_{0,0(0)}}{1 + \dfrac{1}{SF_k} E[(I/N)_{0(0)}]}, \tag{8}$$

where E[.] is the ensemble average operation during a call and $(I/N)_{0(0)}$ is the received interference-to-noise power ratio at the 0(0)-th BS. Neglecting the self-interference due to inter-path interference of own signal, $(I/N)_{0(0)}$ is given by

$$\begin{aligned}(I/N)_{0(0)} &= (U_{0(0)} - 1)\,(S/N)_{target} \\ &\quad + \sum_{\substack{all\ j(i) \\ j(i) \neq 0(0)}} \sum_{i=0}^{U_{j(i)}-1} (P_t/N)_i \cdot r_{i,0(0)}^{-\alpha} \cdot 10^{-\eta_{i,0(0)}/10} \cdot \sum_{l=0}^{L_{eq}-1} \left| \xi_{i,0(0)}(l) \right|^2,\end{aligned} \tag{9}$$

where the first term is the own-cell other-user interference and the second term is the other-cell other-user interference. $U_{j(i)}$ is the number of MSs that are communicating with the $j(i)$-th BS. Substitution of Eqs. (7) and (9) into Eq. (8) gives

$$\gamma = \frac{\left(\dfrac{S}{N}\right)_{target}}{1 + \dfrac{\left(\dfrac{S}{N}\right)_{target}}{SF_k} \cdot E\left[\begin{array}{l} U_{0(0)} - 1 + \displaystyle\sum_{\substack{all\ j(i) \\ j(i) \neq 0(0)}} \sum_{i=0}^{U_{j(i)}-1} \left(\frac{r_{i,j(i)}}{r_{i,0(0)}} \right)^{\alpha} \\ \cdot 10^{\frac{\eta_{i,j(i)} - \eta_{i,0(0)}}{10}} \cdot \left\{ \dfrac{\displaystyle\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j(i)}(l) \right|^2}{\displaystyle\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,0(0)}(l) \right|^2} \right\}^{-1} \end{array} \right]}. \tag{10}$$

This paper assumes that the user location does not change during a call, but the instantaneous signal power varies due to fading. We consider two cases: (1) K=1 and (2) $K > 1$.

(1) K=1

When K=1, since the site selection diversity based on the instantaneous SNR measurement is used (see Eq. (5)), the communicating BS changes during a call. Therefore, U, r, η and ξ in Eq. (10) are random variables. Since we are assuming the uniform power delay profile, we have

$$E\left[\left| \xi_{i,0(0)}(l) \right|^2 \right] = \frac{1}{L_{eq}}. \tag{11}$$

However, since the communicating BS changes during a call, it is not easy to analytically find the expected value of

$$X = \left(r_{i,j(i)}/r_{i,0(0)} \right)^{\alpha} \cdot 10^{(\eta_{i,j(i)} - \eta_{i,0(0)})/10} \cdot \left(\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j(i)}(l) \right|^2 \right)^{-1}$$

in the denominator of Eq. (10). Since X is independent of $\left(\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,0(0)}(l) \right|^2 \right)$, substitution of Eq. (11) into Eq. (10) gives

$$\gamma = \frac{\left(\dfrac{S}{N}\right)_{target}}{1 + \dfrac{\left(\dfrac{S}{N}\right)_{target}}{SF_k} \cdot E\left[\begin{array}{l} U_{0(0)} - 1 + \displaystyle\sum_{\substack{all\ j(i) \\ j(i) \neq 0(0)}} \sum_{i=0}^{U_{j(i)}-1} \left(\frac{r_{i,j(i)}}{r_{i,0(0)}} \right)^{\alpha} \\ \cdot 10^{\frac{\eta_{i,j(i)} - \eta_{i,0(0)}}{10}} \cdot \left(\displaystyle\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j(i)}(l) \right|^2 \right)^{-1} \end{array} \right]}$$

for $K = 1$. (12)

(2) $K > 1$

When $K > 1$, since each MS communicates with a BS having the largest *local average* received signal power, the communicating BS does not change during a call (see Eq. (6)), but the instantaneous signal power varies due to fading. Therefore, the random variable in the denominator of Eq. (10) is ξ only. Since the communicating BS does not change during a call, we can analytically find the expected value of $\left(\sum_{l=0}^{L_{eq}-1} \left| \xi_{i,j(i)}(l) \right|^2 \right)^{-1}$ in Eq. (10). $\left| \xi_{i,j(i)}(l) \right|^2$ is an exponentially distributed random variable with mean $1/L_{eq}$, we have [5]

$$E\left[\left(\sum_{l=0}^{L_{eq}-1}\left|\xi_{i,j(i)}(l)\right|^2\right)^{-1}\right]=\frac{L_{eq}}{L_{eq}-1}. \tag{13}$$

Substitution of Eqs. (11) and (13) into Eq. (10) gives

$$\gamma=\frac{\left(\dfrac{S}{N}\right)_{target}}{1+\dfrac{\left(\dfrac{S}{N}\right)_{target}}{SF_k}\cdot\left\{\begin{array}{l}U_{0(0)}-1+\dfrac{L_{eq}}{L_{eq}-1}\\ \cdot\displaystyle\sum_{\substack{all\ j(i)\\ j(i)\neq 0(0)}}\sum_{i=0}^{U_{j(i)}-1}\left(\frac{r_{i,j(i)}}{r_{i,0(0)}}\right)^{\alpha}\cdot 10^{\frac{\eta_{i,j(i)}-\eta_{i,0(0)}}{10}}\end{array}\right\}}$$

for $K>1$. (14)

Using the Gaussian approximation of the interference, the bit error rate (BER) P_b with QPSK coherent detection is given by [6]

$$P_b=\frac{1}{2}erfc\sqrt{\frac{\gamma}{2}}, \tag{15}$$

from which the required SINR γ_0 can be computed for the given required BER.

3. Computer Simulation

3.1 Simulation model

Table 2 shows simulation parameters. The link capacity is defined as the allowable maximum offered traffic that satisfies the required quality represented by the outage probability. Outage occurs when the frequency allocation fails or when the frequency allocation is successful but the average SINR is less than the required SINR γ_0. Other assumptions are as follows.

(1) Hexagonal cell layout using 37 cells.
(2) Poisson distributed call arrival with mean λ and constant holding period μ.
(3) Interference-limited channel.
(4) When K=1, the same frequency band is reused in all cells. Site diversity based on selection combining is used. When $K>1$, each MS communicates with a BS that provides the largest local average received signal power.

Table 2 Simulation parameters.

Traffic model		Poisson distribution
Data modulation		QPSK
Spreading factor		SF=128
Channel model	Path loss exponent	α=3.5
	Standard deviation of shadowing loss	σ=6dB
	Power delay profile	Uniform
	Number of paths	L=4,8,16,32

3.2 Simulation Results

The probability of the n-th frequency band f_n being used is shown in Fig. 3 for K=4 and L=16. Darker the color becomes, higher the probability becomes. It is seen that different frequency bands tend to be allocated at adjacent cells.

Figure 4 plots the outage probability as a function of offered traffic G (Erl/cell) with K as a parameter. It is seen from this figure that the outage probability highly depends on K and L. As K increases, the number of usable frequency bands increases. The large other-cell interference can be avoided by allocating the other frequency bands at adjacent cells thus the outage probability becomes smaller than that of K=1. However, as K becomes too large, the number of resolvable paths decreases and the path diversity gain obtainable by Rake combining decreases, thereby increasing the outage probability. Therefore, there is an optimum value of K which minimizes the outage probability. An optimum value of K also depends on G. In a large traffic region (i.e., $G>9$, 6 and 4 for L=32, 16 and 8, respectively), the outage probability when K=1 is smaller than that when $K>1$. On the other hand, in a small G region (i.e. $G<9$, 6 and 4 for L=32, 16 and 8, respectively), band division can decrease the outage probability. A possible reason for this can be explained below. When K=1, since site diversity gain can be obtained, the probability of large MS transmit powers is reduced. Therefore, as G increases, the outage probability of K=1 increases more slowly than that of $K>1$. Hence the outage probability when K=1 is smaller than when $K>1$ in a large G region.

Figure 5 plots the link capacity as a function of K with L as a parameter for the allowable outage probability P_{allow} = 10^{-2}, 3×10^{-2} and 10^{-1}. If K=1 is used, site diversity is used to reduce the other cell interference. On the other hand, when $K>1$, instead of site diversity, the different frequency bands are allocated to neighboring cells in order to reduce the other cell interference. However, if too small K is used, e.g., K=2, since some of the surrounding cells may be allocated the same frequency band, the interference

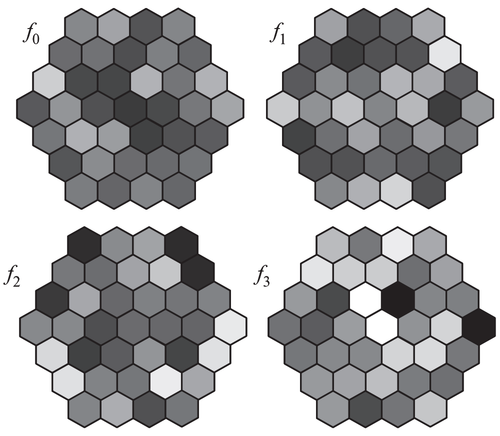
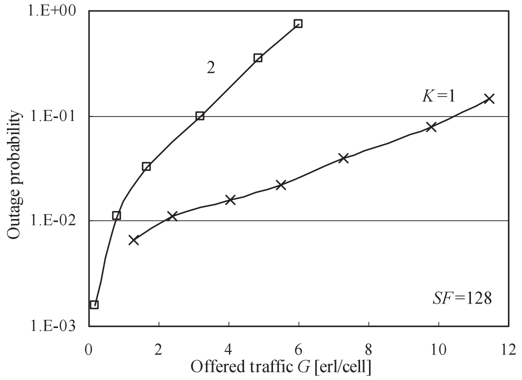
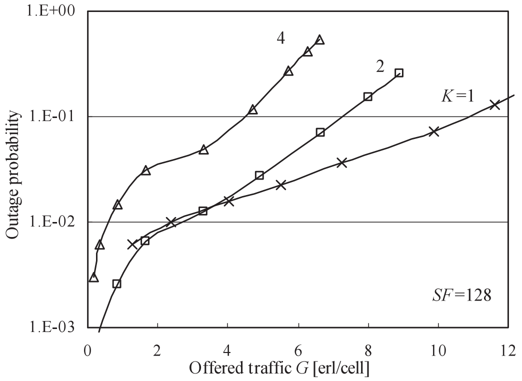


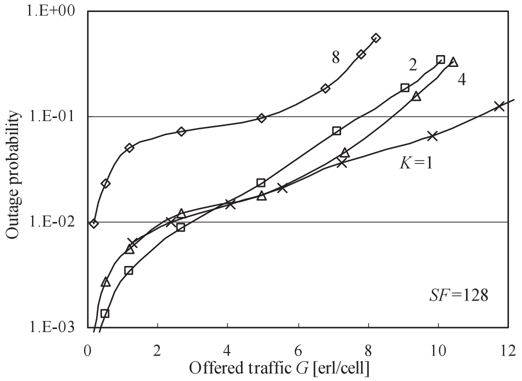
Fig. 3 Frequency band distribution for K=4 and L=16.



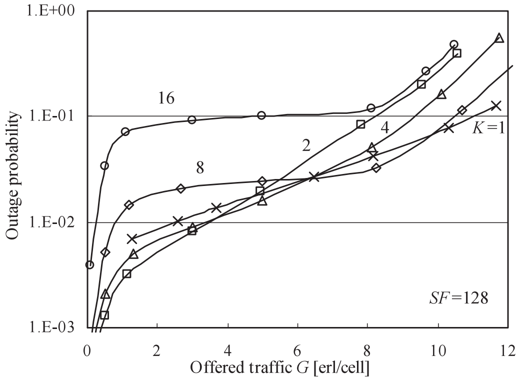
(a) L=4.



(b) L=8.

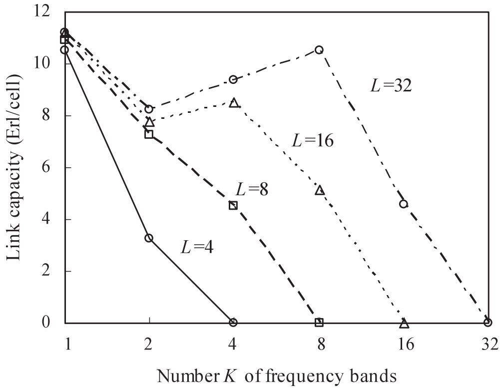


(c) L=16.

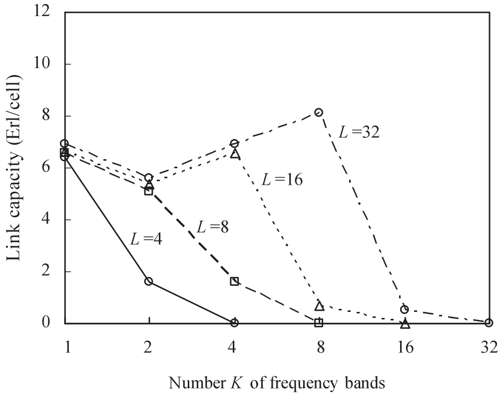


(d) L=32.

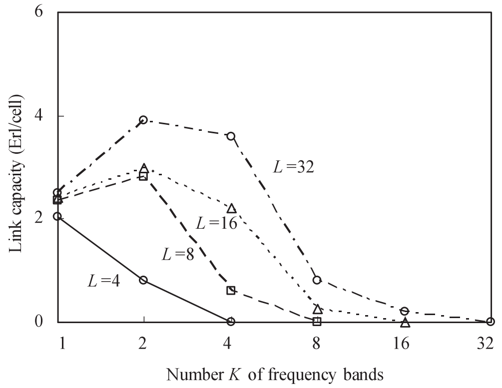
Fig. 4 Outage probability.



(a) $P_{\mathrm{allow}} = 10^{-1}$.



(b) $P_{\mathrm{allow}} = 3 \times 10^{-2}$.



(c) $P_{\mathrm{allow}} = 10^{-2}$.

Fig. 5 Link capacity as a function of K.

reduction is insufficient and hence, the link capacity using band division is smaller than using K=1. As K increases, the interference tends to reduce, thereby increasing the link capacity. If too large K is used, however, the number of resolvable paths reduces because of narrower bandwidth and therefore, the path diversity effect due to Rake combining reduces, thereby decreasing the link capacity. This is seen when L=16 and 32 for $P_{\mathrm{allow}}=10^{-1}$ and also for $P_{\mathrm{allow}} = 3 \times 10^{-2}$. However, for the case of $P_{\mathrm{allow}}=10^{-2}$, the link capacity using K=1 is smaller than using K=2 except when L=4. A possible reason for this is explained below. Since the allowable interference power is very low for the case of $P_{\text{allow}} = 10^{-2}$, only a small number of users can be generally accommodated in each cell; however, large interference may be sometimes produced. Although the band division can avoid this by allocating a different frequency band to an adjacent cell, the site diversity cannot sufficiently suppress such a large interference power below the very low allowable interference power since the same frequency band is used in all adjacent cells.

4. Conclusions

In this paper, a DS-CDMA cellular system with band division and CS-DCA was proposed; the available wide frequency band is divided into several narrow frequency bands and the different frequency bands are allocated by using CS-DCA to adjacent cells so as to avoid the large other-cell interference. The link capacity was evaluated by computer simulation. We have shown that an introduction of band division and CS-DCA into a DS-CDMA cellular system has a potential of increasing the link capacity for the case of small allowable outage probability (i.e., higher quality).

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