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SPECIAL ISSUE PAPER

Combined code reuse scheme with two-dimensional OVSF codes assignment algorithm for uplink multi-user/multi-rate block spread multi-cellular CDMA

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ABSTRACT

The two-dimensional (2D) block spread code division multiple access (CDMA) can avoid the uplink multiple-access interference with low-complexity single-user detection in a slow fading channel and, therefore, is very attractive. In the 2D spreading, orthogonal variable spreading factor (OVSF) is used for spreading; an important problem is how to efficiently assign the limited resource of OVSF codes to users with different data rates, while meeting the requirement of quality of service in a multi-cell environment. In this paper, it is shown that the code reuse can improve the code reuse efficiency and the proposed code reuse scheme combined with code assignment algorithm can allow flexible multi-rate uplink transmission. The computer simulation confirms that the proposed code assignment algorithm improves the code reuse efficiency while achieving lower blocking probability than traditional CDMA. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
two-dimensional block spread CDMA; multi-access interference (MAI); code assignment; code reuse efficiency

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1. INTRODUCTION

In next generation mobile communications systems, a flexible support of multi-rate/multi-user broadband services is demanded [1,2]. This can be achieved by multi-code code division multiple access (multi-code CDMA). The well-known CDMA techniques include single-carrier CDMA (SC-CDMA) by time-domain spreading [3,4] and multi-carrier CDMA (MC-CDMA) by frequency-domain spreading [2,4]. In both kinds of CDMA, the usage of frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion provides good bit error rate (BER) performance in a severe frequency-selective fading channel [5].

For the uplink (mobile to base station (BS)) transmission, because different users' signals are asynchronously received via different fading channels, multiple-access interference (MAI) occurs, which limits the uplink capacity. The two-dimensional (2D) block spread CDMA can be applied to solve the MAI and achieve frequency diversity gain in a frequency-selective fading channel [6]. In the 2D spreading, chip-level spreading and block-level spreading are implemented as different roles. The chip-level spreading plays the same part as traditional SC-(or MC-) CDMA, which can achieve the frequency diversity gain by using MMSE-FDE in the receiver. In 2D block spread CDMA, block-level spreading is performed to each block after chip-level spreading. Before the transmission, the guard interval (GI), which is larger than or equals to the maximum delay among different users, is inserted. At the receiver, after removing the GI, block-level de-spreading is performed in order to remove the MAI. If the maximum timing offset among uses is within the GI length, perfect removal of MAI is possible in the case of block fading (i.e., the channel stays constant during at least one block). Both chip-level spreading codes and block-level spreading codes can be constructed using the orthogonal variable spreading factor (OVSF) code tree [7].

The OVSF code tree has a unique property. The descendant and ancestor codes of the same root code cannot be used simultaneously because any two codes from the same mother code are not orthogonal to each other. Therefore, the OVSF code tree has a limited number of available codes (limited code capacity). Many code assignment algorithms were proposed for CDMA [8–19]. Recently, we proposed a new adaptive code assignment algorithm, which could minimize the code blocking probability due to the code capacity limitation [20]. However, even if the whole spreading codes constructed by OVSF code tree are successfully assigned to users, the received signal-to-interference plus noise power ratio may sometimes drop as a result of fading.

Therefore, the blocking probability is not only caused by the code capacity limitation but also due to the poor quality (i.e., the BER becomes higher than the required BER). Although the code assignment algorithms for a traditional CDMA system have been well studied, few papers investigated the achievable BER performance when code assignment algorithm is used. The code blocking probability is affected by BER performance [14]. However, because the system level evaluation is very complex, most of the papers only considered the code blocking probability caused by code capacity limitation assuming error free transmission. In Ref. [21], the BER performance is taken into account when evaluating the proposed code assignment algorithm, in 2D block spread CDMA system. However, in Ref. [21], only a single cell was considered, and furthermore, a fairly large code space was assumed (i.e., no code limitation exists). To overcome the code limitation problem in a cellular system (i.e., multi-cell environment), a code reuse algorithm was first proposed in paper [22] for 2D block spread cellular CDMA uplink, where the same block-level spreading code was able to be reused in different cells. Reference [22] does not provide theoretical analysis of the code reuse scheme in 2D block spread CDMA because of page limitation, and only discusses the block-level spreading factor reuse algorithm with the assumption that the same data rate for all users. This paper provides a theoretical analysis of the code assignment problems for 2D block spread CDMA in a multi-cell environment and considers different data rates. The main contributions in this paper are as follows:

(1) The code reuse scheme is proposed for 2D block spread CDMA in multi-cell environment. The code reuse region is theoretically discussed.
(2) The code assignment algorithm is presented taking into account both the chip-level spreading and block-level spreading. Impact of chip-level and block-level spreading factor on the BER performance is discussed.

The remainder of the paper is organized as follows. Section 2 briefly discusses the 2D code assignment and blocking in 2D block spread CDMA. The uplink transmission model is presented in Section 3. Then, the code reuse algorithm is proposed in Section 4. In Section 5, simulation results on code reuse efficiency and blocking probability are discussed. Section 6 offers some concluding remarks.

2. PRELIMINARY AND DEFINITIONS

2.1. Two-dimensional code assignment

Figure 1 illustrates the OVSF code tree [7]; $C_{p,k}$ denotes an OVSF code of the kth ($k = 0, 1, \ldots, 2^{p-1} - 1$) code in the pth layer. The root code is denoted as $C_{1,0} = (1)$ and the second layer has two codes, $C_{2,0} = (1, 1)$ and $C_{2,1} = (1, -1)$. The codes in the pth layer are generated as $\left(C, \overline{C}\right)$ from each code C of the $(p-1)$th layer; here, $\overline{C}$ is the bit-wise complement of C. The number of available codes in the pth layer is 2^{p-1}, which is the same as the spreading factor of the layer; thus, the number of orthogonal codes increases with the increasing layer. All codes in the same layer are orthogonal to each other, whereas codes in different layers are orthogonal only if they do not have the same mother code. Thereby, to avoid MAI in uplink 2D block spread CDMA, orthogonal codes, that is, the codes in the same layer, are necessary for block-level spreading.

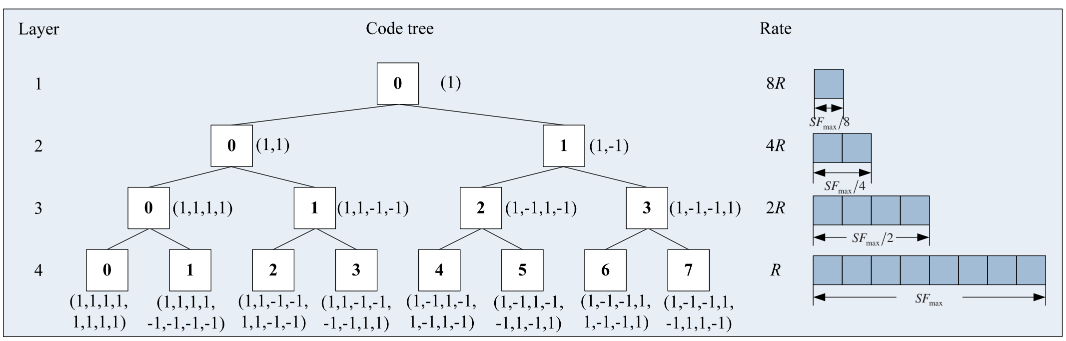

Figure 1. Orthogonal variable spreading factor code tree and an example to show the relationship between the code tree and the data rate.

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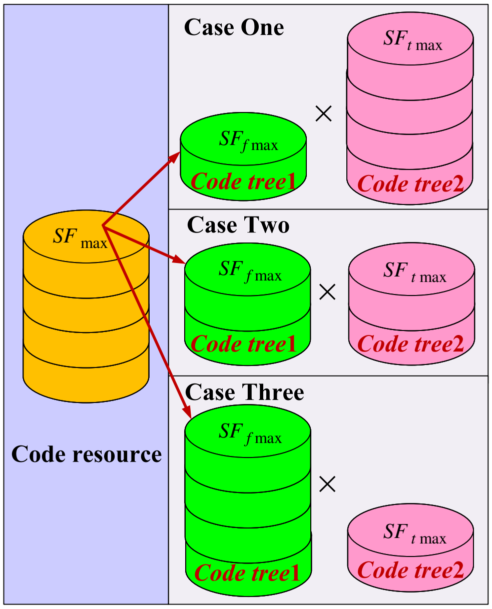

Figure 2. Different combinations of SF_{max}, $SF_{f\,max}$, and $SF_{t\,max}$.

In this paper, two code trees are used for both chip-level spreading and blocking spreading; suppose that $SF_{f\,max}$ and $SF_{t\,max}$ are the maximum number of chip-level spreading factor and block-level spreading factor, respectively, and set $SF_{max} = SF_{f\,max} \times SF_{t\,max}$ as a constant determined by the system design, an example to show the relationship between SF_{max}, $SF_{f\,max}$, and $SF_{t\,max}$ is shown in Figure 2. This paper presents the code assignment in multi-rate transmission.

One advantage of CDMA is to provide flexible multi-rates transmission by selecting different spreading factors. For example, assume that the lowest data rate is R and the chip time is T_c. So, if a code from the fourth layer (as shown in Figure 1) is chosen, it needs $8T_c$ to transmit one data; moreover, if a code from the third layer is selected, it takes $4T_c$ that can support the data rate $2R$. It can be derived that the spreading factor is inverse of the data rate; hence, the highest layer supports the lowest data rate, and the lowest layer provides the highest data rate (as shown in Figure 1). In this paper, we assume that the lowest data rate R needs $SF_{max} \cdot T_c$ chip time, for mathematical convenience, taking SF_{max} instead of $SF_{max} \cdot T_c$. Here, SF_{max} is the maximum number of spreading factor. If the data rate R_u of the uth user is C_u times the lowest rate, the spreading factor of the uth user is given by

$$SF_u = \frac{SF_{max}}{C_u} \tag{1}$$

To describe the presented algorithm clearly, Table I lists the variables used in this paper.

2.2. Blocking probability

Sometimes users cannot be served (or blocked) because of the capacity limitation of the OVSF code tree. Even if a user is successfully assigned a code, its transmission quality may drop below the required quality of service (QoS). In this paper, the transmission quality is represented by the BER. If the BER of user u becomes higher than the required BER_{req}, user u is declared to be blocked.

The blocking probability P_{block} is defined as

$$P_{block} = \frac{U_{block\_by\_CodeLimited} + U_{block\_by\_FaildedInQoS}}{U_{total\_come}} \tag{2}$$

where $U_{block\_by\_CodeLimited}$ is the total number of users who could not be served because of the code capacity limitation, $U_{block\_by\_FaildedInQoS}$ denotes as the total number of users whose link quality worse than the required QoS, and U_{total_come} denotes the total number of arrival users over a measurement time interval.

3. UPLINK TRANSMISSION MODEL

The uplink transmitter/receiver structure of 2D block spread direct sequence CDMA is shown in Figure 3.

Table I. Parameters.

R	Lowest data rate
$R_u(R_u = C_u \cdot R)$	Data rate of uth user, which is C_u times the lowest data rate R.
SF_{max}	Maximum spreading factor
$SF_{f\,max}$	Maximum chip-level spreading factor
$SF_{t\,max}$	Maximum block-level spreading factor
$SF_u(SF_u = SF_{u,f} \times SF_{u,t})$	Total spreading factor of the uth user
$SF_{u,f}(1 \le SF_{u,f} \le SF_{f\,max})$	Chip-level spreading of the uth user
$SF_{u,t}(1 \le SF_{u,t} \le SF_{t\,max})$	Block-level spreading of the uth user
$\left\{c_{b\_u}^{SF_{u,f}}(t); t = 0 \sim SF_{u,f} - 1\right\}$	Chip-level spreading code sequence of the uth user in the bth cell
$\left\{c_{b\_u}^{SF_{u,t}}(t); t = 0 \sim SF_{u,t} - 1\right\}$	Block-level spreading code sequence of the uth user in the bth cell
P_{block}	Blocking probability
$U_{block\_by\_CodeLimited}$	No. of blocked users due to code capacity limitation
$U_{block\_by\_FaildedInQoS}$	No. of blocked users due to poor quality of service
U_{total_come}	No. of arrival users in a measurement time interval

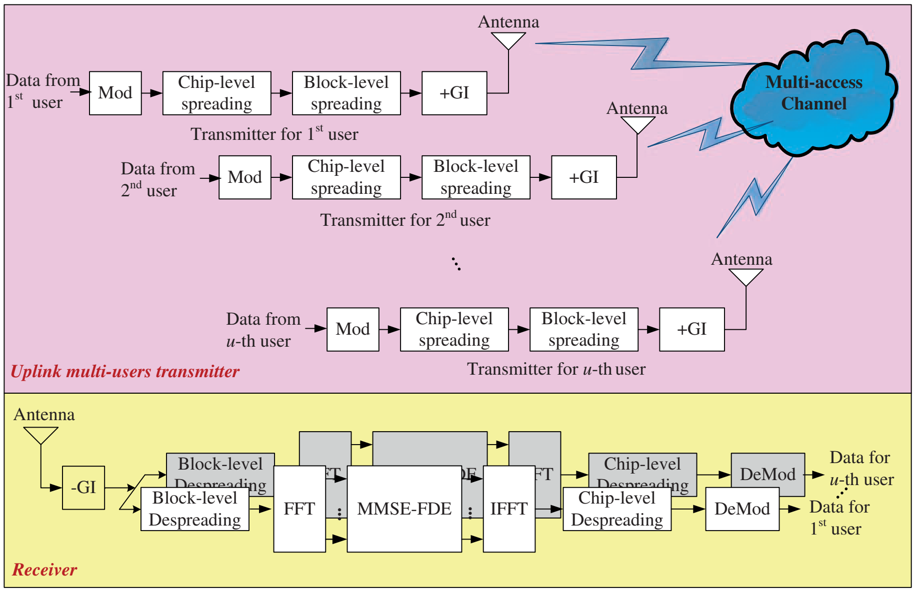

Figure 3. Uplink transmitter/receiver structure of 2D block spread direct sequence code division multiple access. GI, guard interval; FFT, fast Fourier transform; MMSE, minimum mean square error; FDE, frequency-domain equalization; IFFT, inverse fast Fourier transform.

In the receiver, the block-level de-spreading is first performed to remove the MAI, and the fast Fourier transform (FFT) algorithm transforms the received signal block into frequency-domain signal so that FDE is applied to achieve the frequency diversity. A detailed description of 2D block spread CDMA can be found in Ref. [6].

In the following discussion, the spreading factors of chip-level and block-level spreading for the uth user are denoted by $SF_{u,f}$ and $SF_{u,t}$, respectively, whereas the total spreading factor of the uth user is $SF_u (= SF_{u,f} \times SF_{u,t})$. In this paper, $\lceil a \rceil$ represents the largest integer smaller than or equal to a; $\lfloor a \rfloor$ is the smallest integer larger than a.

3.1. Transmission signal

The data symbol sequence to be transmitted from the uth user in the bth cell is denoted by $\{d_{b\_u}(n);\ n = 0 \sim N_c/SF_{u,f} - 1\}$, where N_c is the block size of FFT at a receiver. The data symbol sequence to be transmitted is spread by chip-level spreading code sequence $\left\{c^{SF_{u,f}}_{b\_u}(t); t = 0 \sim SF_{u,f} - 1\right\}$ with $\left|c^{SF_{u,f}}_{b\_u}(t)\right| = 1$ and is further multiplied by a binary scramble sequence $\left\{c^{\mathrm{scr}}_{b\_u}(t); t = 0 \sim N_c - 1\right\}$ to make the resultant signal white-noise like. The resultant SC-CDMA chip sequence $\left\{s^{\mathrm{SC}}_{b\_u}(t); t = 0 \sim 2N_c - 1\right\}$ is expressed as

$$s^{\mathrm{SC}}_{b\_u}(t) = c^{\mathrm{scr}}_{b\_u}(t) \cdot d_{b\_u}\left(\lfloor t/SF_f \rfloor\right) c^{SF_{u,f}}_{b\_u}\left(t \bmod SF_{u,f}\right) \tag{3}$$

In the block-level spreading, each N_c-chip block is repeated $SF_{u,t}$ times, and each block is multiplied by a chip taken from an orthogonal block-level spreading code sequence $\left\{c^{SF_{u,t}}_{b\_u}(t); t = 0 \sim SF_{u,t} - 1\right\}$, which is used by the uth user in the bth cell. The equivalent lowpass representation can be expressed as

$$\widehat{s}_{b\_u}(t) = \sqrt{2P_{b\_u}} \cdot s^{\mathrm{SC}}_{b\_u}(t \bmod N_c)\, c^{SF_{u,t}}_{b\_u}\left(\lfloor t/N_c \rfloor\right) \tag{4}$$

for $t = 0 \sim SF_{u,t} \times N_c - 1$, where P_{b_u} is the transmit power of the uth user belonging to the bth cell. After inserting an N_g-chip GI in every N_c-chip block, a sequence of N_c-chip blocks is transmitted over a frequency-selective fading channel.

3.2. Received signal

The GI inserted signal is transmitted over a frequency- and time-selective fading channel. Assuming a channel with chip-spaced L independent paths, its impulse response $h_{b\_u}(\tau)$ of the channel between the uth user in the bth cell, and its corresponding BS is expressed as

$$h_{b\_u}(\tau) = \sum_{l=0}^{L-1} h_{b\_u,l}\, \delta\left(\tau - \tau_{b\_u,l}\right) \tag{5}$$

where $h_{b\_u,l}$ and $\tau_{b\_u,l}$ are respectively the complex-valued path gain and time delay of the lth path. In this paper, it is assumed that $h_{b\_u,l}$ stays unchanged during block interval $T = T_c(N_c + N_g)$, but it changes block by block, $\tau_{b\_u,l}$ is equal to $\tau_{b\_u,l} = \tau_{b\_u} + l \cdot T_c$ $(l = 0 \sim L - 1)$ with T_c being the chip length, and τ_{b_u} is the transmit timing offset. The maximum time delay is assumed to be shorter than the GI.

The sum of users' faded signals is received at the bth cell BS, and the GI-removed received signal can be expressed as

$$r(t)=\sum_{b=0}^{B-1}\sum_{u=0}^{U_b-1}\sum_{l=0}^{L-1} h_{b\_u,l}\hat{s}_{b\_u}\left(t-\tau_{u,l}\right)+n(t) \quad (6)$$

for $t=0\sim N_c\cdot SF_{t,\max}-1$, where $n(t)$ is the zero-mean complex-valued noise samples due to the additive white Gaussian noise (AWGN) with variance $2N_0/T_c$ (N_0 is the AWGN one-sided power spectrum density), B is the number of cells, and U_b is the number of arriving users in a time interval of $SF_{t,\max}$ consecutive blocks in the bth cell.

To recover the transmission SC-CDMA signal of the uth user, block-level de-spreading is carried out first as $r_{b\_u}(t)=(1/SF_{t,\max})\cdot\sum_{i=0}^{SF_{t,\max}-1}r(t+iN_c)\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*$ for $t=0\sim N_c-1$. Because a block fading (i.e., path gains stay almost constant over a time interval of $SF_{t,\max}$ consecutive blocks) is assumed, it can be derived that

$$\begin{aligned}r_{b\_u}(t)=&\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\sum_{l=0}^{L-1}h_{b\_u,l}\hat{s}_{b\_u}\left(t+iN_c-\tau_{u,l}\right)\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\\&+\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\sum_{\substack{u'=0\\u'\neq u}}^{U_b-1}\sum_{l=0}^{L-1}h_{b\_u',l}\hat{s}_{b\_u'}\left(t+iN_c-\tau_{u',l}\right)\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\\&+\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\left\{\sum_{\substack{b'=0\\b'\neq b}}^{B-1}\sum_{u'=0}^{U_{b'}-1}\sum_{l=0}^{L-1}h_{b'\_u',l}\hat{s}_{b'\_u'}\left(t+iN_c-\tau_{u',l}\right)\right\}\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\\&+\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}n\left(t+iN_c\right)\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\end{aligned}\quad (7)$$

The first, second, third, and fourth terms in Equation (7) are the desired signal, MAI from other users in its own cell, MAI from other users in other cells, and noise, respectively. The first, second, and third terms can be respectively written as

$$\text{Desired signal}=\sqrt{2P_{b\_u}}\sum_{l=0}^{L-1}h_{b\_u,l}\cdot s_{b\_u}^{SC}\cdot\left\{\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\left\{c_{b\_u}^{SF_{u,t}}\right\}\cdot\left\{c_{b\_u}^{SF_{u,t\max}}\right\}\right\}=\sqrt{2P_{b\_u}}\sum_{l=0}^{L-1}h_{b\_u,l}\cdot s_{b\_u}^{SC} \quad (8a)$$

$$\begin{aligned}MAI_{\text{own-cell}}=&\frac{\sqrt{2P_{b\_u'}}}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\sum_{\substack{u'=0\\u'\neq u}}^{U_b-1}\sum_{l=0}^{L-1}h_{b\_u',l}\cdot s_{b\_u'}^{SC}\cdot\left\{c_{b\_u'}^{SF_{u',t}}\right\}\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\\=&\sqrt{2P_{b\_u'}}\sum_{\substack{u'=0\\u'\neq u}}^{U_b-1}\sum_{l=0}^{L-1}h_{b\_u',l}s_{b\_u'}^{SC}\left\{\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\left\{c_{b\_u'}^{SF_{u',t}}\right\}\cdot\left\{c_{b\_u'}^{SF_{u,t\max}}\right\}^*\right\}\end{aligned}\quad (8b)$$

$$\begin{aligned}MAI_{\text{other-cells}}=&\frac{\sqrt{2P_{b'\_u'}}}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\left\{\sum_{\substack{b'=0\\b'\neq b}}^{B-1}\sum_{u'=0}^{U_{b'}-1}\sum_{l=0}^{L-1}h_{b'\_u',l}\cdot s_{b'\_u'}^{SC}\cdot\left\{c_{b'\_u'}^{SF_{u,t}}\right\}\right\}\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\\=&\sqrt{2P_{b'\_u'}}\sum_{\substack{b'=0\\b'\neq b}}^{B-1}\sum_{u'=0}^{U_{b'}-1}\sum_{l=0}^{L-1}h_{b'\_u',l}\cdot s_{b'\_u'}^{SC}\cdot\left\{\frac{1}{SF_{t,\max}}\sum_{i=0}^{SF_{t,\max}-1}\left\{c_{b'\_u'}^{SF_{u,t}}\right\}\cdot\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*\right\}\end{aligned}\quad (8c)$$

Each user is assigned with orthogonal block-level spreading code. It is assumed that the maximum time delay among different users in the same cell (including the time delay difference of propagation channels) is shorter than the GI length. Furthermore, it is supposed that the fading is slow enough and the path gains stay almost unchanged over at least $SF_{t,\max}$ consecutive blocks. Because the block-level spreading codes $\left\{c_{b\_u}^{SF_{u,t}}(t)\right\}$ are orthogonal to each other, we have $(1/SF_{t,\max})\cdot\sum_{i=0}^{SF_{t,\max}-1}\left\{c_{b\_u'}^{SF_{u',t}}\right\}\cdot\left\{c_{b\_u}^{SF_{u,t\max}}\right\}^*=0(u\neq u')$ and, therefore, $MAI_{\text{own-cell}}=0$. However, $MAI_{\text{other-cell}}$ cannot be zero because of insufficient number of block-level spreading codes. Hence, the same block-level spreading codes need to be reused. As a consequence, we can have

$$\begin{aligned} r_{b\_u}(t) &= \sqrt{2P_{b\_u}} \sum_{l=0}^{L-1} h_{b\_u,l} \cdot s_{b\_u}^{\mathrm{SC}} \\ &+ \sqrt{2P_{b'\_u'}} \sum_{\substack{b'=0 \\ b' \neq b}}^{B-1} \sum_{u'=0}^{U_{b'}-1} \sum_{l=0}^{L-1} h_{b'\_u',l} \cdot s_{b'\_u'}^{\mathrm{SC}} \\ &\cdot \left\{ \frac{1}{SF_{t,\max}} \sum_{i=0}^{SF_{t,\max}-1} \left\{ c_{b'\_u'}^{SF_{u,t}} \right\} \cdot \left\{ c_{b\_u}^{SF_{u,t\max}} \right\}^* \right\} \\ &+ \frac{1}{SF_{t,\max}} \sum_{i=0}^{SF_{t,\max}-1} n\left(t + iN_{\mathrm{c}}\right) \left\{ c_{b\_u}^{SF_{u,t\max}} \right\}^* \end{aligned} \tag{9}$$

After block-level de-spreading, the frequency-domain chip equalization and chip-level de-spreading are carried out similar to the traditional CDMA.

3.3. Reuse of block-level spreading codes

For uplink 2D block spread CDMA, the users in the same cell are assigned different block-level spreading codes to avoid MAI. The same block-level spreading codes can be reused in different cells. In this paper, we assume that slow transmit power control (TPC) is adopted, so that the average received signal power at the BS is always kept the same for all users in the same cell.

The code reuse efficiency is defined as the average reuse number of the same block-level spreading code per cell (if the same block-level spreading code is reused in all the cells and the code reuse factor is one). The interference model is illustrated in Figure 4.

The distance between the BS and the uth user in the bth cell ($b = 0 \sim (B-1)$) is denoted by D_{b_u}, where the $b = 0^{\text{th}}$ cell is assumed to be a cell of interest. Assuming the perfect slow TPC and neglecting the shadowing, the average received signal power at the bth cell BS is given as

$$P_{b\_u} D_{b\_u}^{-\alpha} = P \tag{10}$$

where P is the TPC target and α is the path loss exponent, which is $2 \sim 4$ in an urban area [23,24]. The average received signal power is kept as P for all users in the same cell.

Regarding Equation (7), the frequency-domain representation of the received signal for the uth user in the bth cell is given as

$$\begin{aligned} R_{b\_u}(k) &= \sqrt{2P} \cdot S_{b\_u}(k) H_{b\_u}(k) \\ &+ \sqrt{2P} \sum_{\substack{u'=0 \\ u'(b') \neq u}}^{U_b-1} S_{b\_u'(b')}(k) Z_{b\_u'(b')}(k) \\ &+ \sum_{\substack{b'=0 \\ b' \neq b}}^{B-1} \sum_{u'(b')=0}^{U_{b'}-1} \left(\frac{D_{b'\_u'(b')}}{D_{b\_u'(b')}} \right)^{\alpha} \\ &\cdot \sqrt{2P} S_{b'\_u'(b')}(k) Z_{b'\_u'(b')}(k) + \Pi_{b\_u}(k) \end{aligned} \tag{11}$$

where $S_{b\_u}(k)$ is the kth frequency component of the uth user's transmit signal to the bth BS, and $R_{b\_u}(k)$, $\Pi_{b\_u}(k)$, and $H_{b\_u}(k)$ are respectively the received signal after block-level de-spreading, noise due to the AWGN, and the channel gain at the kth frequency. The second and third terms in Equation (11) are the MAIs from other users in its own cell and in other cells, respectively. $Z_{b'\_u'}(k)$ is the frequency-domain MAI after block-level de-spreading and is given by

$$\begin{aligned} & Z_{b'\_u'(b')}(k) \\ &= \frac{1}{SF_{t\max}} \sum_{i=0}^{SF_{t\max}-1} \left\{ c_{b'\_u'(b')}^{SF_{u',t}}(i) \left\{ c_{b\_u}^{SF_{u,t}}(i) \right\}^* \right. \\ &\quad \left. \times \left[\sum_{l=0}^{L-1} h_{b'\_u'(b'),l} \exp\left(-j2\pi k \frac{\tau_{b'\_u'(b'),l}}{N_{\mathrm{c}}} \right) \right] \right\} \end{aligned} \tag{12}$$

Because $H_{b\_u}(k)$, $S_{b\_u}(k)$, and $Z_{b'\_u'}(k)$ are zero-mean complex Gaussian processes, the sum of the second, third, and fourth terms in Equation (11) can be regarded as a new zero-mean complex Gaussian variable with variance $2\sigma^2$, which is given by

$$\begin{aligned} 2\sigma^2 &= 2P^2 \sum_{\substack{u'=0 \\ u'(b') \neq u}}^{U_b-1} E\left[\left| Z_{b\_u'(b')}(k) \right|^2 \right] \\ &+ 2P^2 \cdot \left(\frac{D_{b'\_u'(b')}}{D_{b\_u'(b')}} \right)^{2\alpha} \sum_{\substack{b'=0 \\ b' \neq b}}^{B-1} \sum_{u'(b')=0}^{U_{b'}-1} \\ &\times E\left[\left| Z_{b'\_u'(b')}(k) \right|^2 \right] + 2\sigma_{\mathrm{AWGN}}^2 \end{aligned} \tag{13}$$

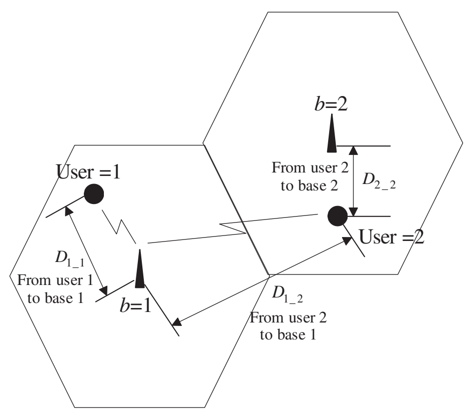

Figure 4. Interference model of two adjacent cells.

where the first and second terms represent the variances of the MAI from the own cell and from the other cells, respectively, and $2\sigma^2_{\mathrm{AWGN}}$ is the noise variance ($E[\cdot]$ denotes the ensemble average operation). $E\left[\left|Z_{b'\_u'(b')}(k)\right|^2\right]$ is given as

$$E\left[\left|Z_{b'\_u'}(k)\right|^2\right] = \frac{1}{(SF_{t\,\max})^2}\sum_{i=0}^{SF_{t\,\max}-1}\sum_{i'=0}^{SF_{t\,\max}-1} \times\left\{J_0\left(2\pi\left|i-i'\right| f_D^{b'\_u'}T\right)\left[C_{b'\_u'}^{SF_{t\,\max}}(i)C_{b\_u}^{SF_{t\,\max}}(i') \times\left\{C_{b'\_u'}^{SF_{b'\_u',t}}(i)C_{b\_u}^{SF_{b\_u,t}}(i')\right\}^*\right]\right\} \tag{14}$$

where $f_D^{b\_u'}$ is the maximum Doppler frequency of the u'th user in the bth cell and $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind (the Jakes propagation model [25] is assumed).

In the case of block fading (i.e., $f_D^{b\_u'} = 0$), because block-level spreading codes are orthogonal to each other, the second term of Equation (14) becomes zero and the MAI from other users in the own cell can be removed. However, because the number of orthogonal codes is limited, the same block-level spreading code must be reused in different cells, and therefore, the MAI is produced from users in other cells.

We define the distance ratio $\Lambda = D_{b'\_u'(b')}/D_{b\_u'(b')}$ ($0 < \Lambda \leq 1$; $\Lambda = 0$ when the location of u' is at the BS of b'; $\Lambda = 1$ when the location of u' is at the borderline between BS b and b'). If Λ is small enough, the second term variance of Equation (13) is negligibly small and, therefore, the BER becomes small enough. Let Λ_0 be the largest allowable Λ, which satisfies the required QoSs. If $\Lambda \leq \Lambda_0$, the same spreading code can be reused in other cells. As Λ reduces, the third term of Equation (11) becomes weaker; when $D_{b'\_u'(b')} \to 0$, the MAI can be negligibly small even if the u'th user in the b'th cell is assigned the same block-level spreading code as the uth user in the bth cell. What should be paid attention is that besides path loss, the shadowing loss will also affect the boundary of the reused area of the same spreading code for adjacent cells. However, the shadowing loss is log-normal distribution with standard deviation 8 dB in urban macro environment [26], which can be viewed as independent of the distances (between users and BS). Hence, for mathematical convenience, the shadowing is ignored.

In order to find the boundary of the areas where the same spreading code can be reused, two adjacent cells are considered (shown in Figure 5), where the bth BS and the b'th BS are located at $(-a, 0)$ and $(a, 0)$, respectively. The u'th user location (x, y) must satisfy the following condition to meet the required QoS.

$$\frac{(x-a)^2+y^2}{(x+a)^2+y^2} \leq \Lambda_0^2 \tag{15}$$

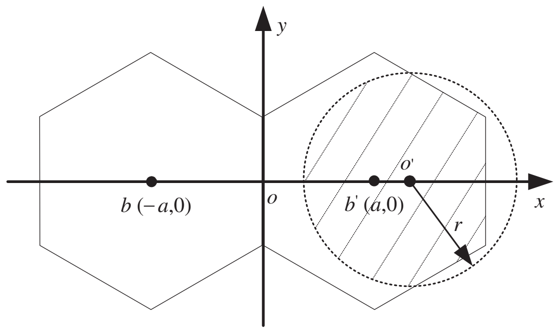

Figure 5. The boundary of the reused area of the same spreading code for two adjacent cells.

When $\Lambda \neq 1$, Equation (15) becomes

$$\left[x - \frac{1+\Lambda_0^2}{1-\Lambda_0^2}a\right]^2 + y^2 \leq \left(\frac{2a\cdot\Lambda_0}{1-\Lambda_0^2}\right)^2 \tag{16}$$

The boundary is a circle with its centre O' and radius r (as shown in Figure 5), and O' and r are given as

$$\begin{cases} O' = \left(\dfrac{1+\Lambda^2}{1-\Lambda^2}a, 0\right) \\ r = \dfrac{2a}{1/\Lambda - \Lambda} \end{cases} \tag{17}$$

Note that r increases as $\Lambda (0 < \Lambda < 1)$ increases. It means that when the required BER is not too low, the corresponding Λ becomes large and, therefore, the range (inside the circle whose center and radius are $O'$and r, respectively) of the interfering u'th user, which can be assigned with the same spreading codes become large.

The analytical results from the two adjacent cells can be extended to the situation including seven cells, and the same spreading code can be assigned to different users in different cells simultaneously with the conditions of

$$\begin{cases} \dfrac{D_{b'\_u'}}{D_{b\_u'}} \leq \Lambda_0 \\ \dfrac{D_{b\_u}}{D_{b'\_u}} \leq \Lambda_0 \end{cases} \tag{18}$$

where $u' = 0 \sim U_{b'} - 1 (u' \neq u)$ and $b' = 0 \sim 6$ $(b' \neq b)$.

4. PROPOSED CODE ASSIGNMENT ALGORITHM

The proposed code assignment algorithm consists of two parts: one is the code reuse algorithm (from step 1 to step 4) to assign the available codes for each cell and the other is the 2D code assignment algorithm (from step 5 to step 10) to realize multi-rate transmission.

Assuming a hexagonal cell layout, BS $b = 0$ is a BS of interested and BS $b = 1 \sim 6$ represent the adjacent BSs because the MAI from the adjacent BS is much stronger than that of non-adjacent cells, which can be almost ignored. In this paper, it is assumed that perfect information of all users' locations is available. The code reuse algorithm consists of the following four steps (from step 1 to step 4) shown in Figure 6. Whenever a new user arrives, the code reuse assignment scheme is started all over again.

Step 1: Initial $m = 0$, here, m is the number of used block-level spreading factor, which could not be larger than $SF_{\max}$. m is used to statistics the possible available block-level codes for cell $b = 0$.

Step 2: Choose a code randomly from the block-level spreading code set, which has not been used by BS $b = 0$ and has not been checked yet. If the chosen code is different from the codes, which have been selected, then $m = m+1$. If m is larger than $SF_{\max}$, the user is blocked. This step is used to find a code (from block-level code tree), which has not been assigned in the appointed cell.

Step 3: Check if the chosen code is already in use by one of six neighbor BSs ($b = 1 \sim 6$). If yes, go to step 4; otherwise, go to step 2.

Step 4: Check if two users of BS $b = 0$ and a neighbor BS $b \neq 0$ satisfy Equation (18). If yes, assign the chosen code to the new user. If not, go to step 1 again and choose the next code. By steps 3 and 4, it is able to derive that whether the selected code by step 2 can be used in multi-cell.

If any block-level code cannot be assigned by the algorithm, it is declared that this user is blocked. After the code reuse assignment (from step 1 to step 4), the OVSF codes are initially allocated

```
Init (m=0, u=0)
Procedure
1)  for each new arrival user u
2)      do u-th user ← C[m]
3)      if C[m] is used by other users
4)         then  m = m+1;
5)               u-th user ← C[m];
6)               if (m>SF_max)
7)                     then blocking record & go to End;
8)         for b =1 to b=6
9)             do to see whether C[m] meet the condition given in equation (18).
10)              if statisfy equation(18)
11)                  then u-th user ← C[m];
12)                       u = u+1;
13)              else m = m+1 & go to 3);
14) End;
```

Figure 6. Code reuse scheme for block-level spreading.

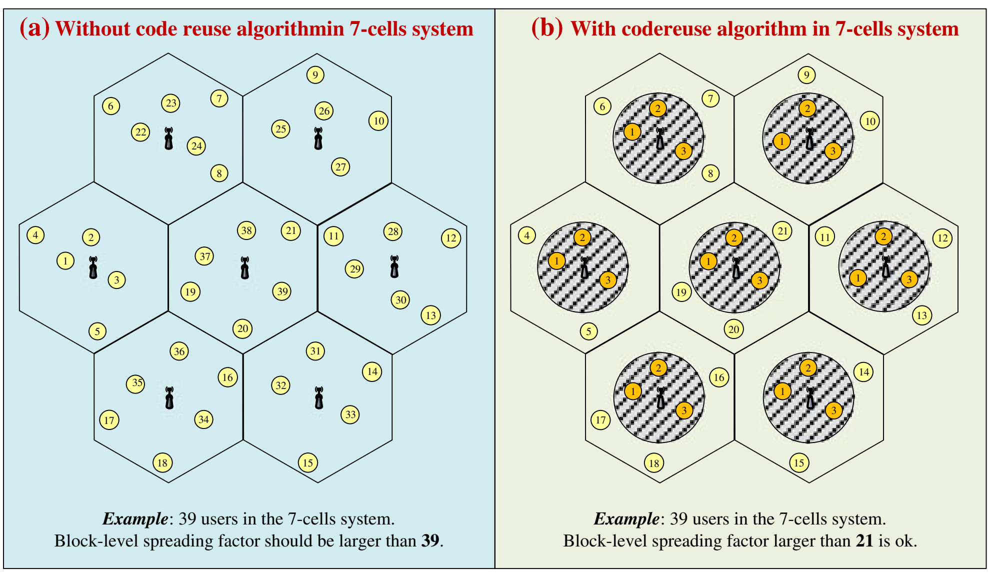

Figure 7. An example to show with or without code reuse scheme.

```
Init (N=0, u=0, U_b)

    do rank the users in the ascending order of data rate
Procedure
1)  for each user u mentioned in code reuse schme
2)        if u < U_b
3)            if SF_fmax >= C_u;
4)                then SF_u,f = SF_fmax/C_u ; SF_u,t = SF_tmax ;
5)                      N = N +1;
6)                      if N <= SF_tmax
7)                          then u = u +1 & go to 2).
8)                      else go to End;
9)            else
10)               SF_u,f = 1; SF_u,t = SF_tmax/(C_u/SF_fmax);
11)               N = N +C_u/SF_fmax ;
12)               if N <= SF_tmax
13)                   then u = u +1 & go to 2).
14)               else go to End;
15) End;
```

Figure 8. Two-dimensional block code assignment algorithm.

to different cells. Figure 7 presents an example to show the differences between the cases with or without code reuse scheme. Assume that 39 users randomly locate in the seven-cell system, if without code reuse scheme, 39 different block-level spreading codes are necessary as shown in Figure 7(a), whereas for the situation with code reuse scheme, the number of block-level spreading codes is 21.

The following six steps (from step 5 to step 10) are used to realize multi-rate transmission shown in Figure 8. The values of $SF_{f\,\max}$ and $SF_{t\,\max}$ should be a power exponent of 2 because OVSF is used for both the chip-level spreading and block-level spreading. Considering m is a randomly integer, set $SF_{t\,\max}$ equals to $2^{\lceil \log_2 m \rceil}$. According to the equation $SF_{\max} = SF_{f\,\max} \times SF_{t\,\max}$, it is easi to get $SF_{f\,\max} = SF_{\max}/SF_{t\,\max}$. The determined code space ($SF_{f\,\max}$ and $SF_{t\,\max}$) are used to assign OVSF codes for flexible multi-rate uplink transmission. Here, U_{serv} is the number of users (which is less than U_b determined by step 8 or step 9) who can be served with its requested data rate C_u.

Step 5: Rank the new users in the ascending order of data rate (low-to-high) according to its requested date rates. To support high data rate, a large code space would be occupied. Hence, in order to serve more users, the user with low data rate has priority than the user with high data rate. Set the code counter $N = 0$ and the user counter $u = 0$. N and u (with data rate $C_u R$) cannot be larger than $SF_{t\,\max}$ and U_b, respectively. Here, code counter and user counter are used to record the number of code resource that have been occupied and the users who have been served, respectively.

Step 6: Check if $u > U_b$. If $u > U_b$, the code assignment is completed (all the users are successfully assigned different codes); else go to step 7.

Step 7: Check if $SF_{f\,\max}$ is equal to or larger than C_u which is the user's requested data rate. If $SF_{f\,\max}$ is larger than C_u, go to step 8, else go to step 9.

Step 8: Set $SF_{u,f} = SF_{f\,\max}/C_u$, $SF_{u,t} = SF_{t\,\max}$ (because $SF_{f\,\max}$ is larger than C_u according to step 7, the requested data rate can be achieved by changing the chip-level spreading factor). Set $N = N + 1$. If $N > SF_{t\,\max}$, the remaining users are blocked and go to step 10; else, choose a user $u = u + 1$ and go to step 6 to do the processing again.

Step 9: Set $SF_{u,f} = 1$ and $SF_{u,t} = SF_{t\,\max}/(C_u/SF_{f\,\max})$ (in this case, the requested data rate cannot be approached by changing the chip-level spreading factor). Set $N = N + C_u/SF_{f\,\max}$ and check if $N > SF_{t\,\max}$ (i.e., an enough number of codes do not exist in the code space and therefore, the uth user cannot be assigned a code that can achieve its required data rate C_u). If $N > SF_{t\,\max}$, the uth user is blocked and go to step 10. Else, sufficient number of codes exist in the code space, and therefore, the uth user can be assigned a code to achieve its required data rate C_u. Then, choose another user $u = u+1$ and go to step 6.

Step 10: End of the code assignment.

5. SIMULATION RESULTS

5.1. Simulation conditions

The performance of the proposed algorithm for 2D block spread SC-CDMA is evaluated by computer simulation.

Table II. Simulation condition.

Transmitter	Modulation	QPSK
	Chip-block length (no. of FFT points)	$N_c = 256$
	GI length	$N_g = 32$
	Spreading codes	Walsh sequences
	Spreading factor	$SF_{max} = 128$
Channel	Type of fading	Rayleigh
	Power delay profile	$L = 16$-path uniform
	Maximum Doppler frequency	$f_D(N_c + N_g)T_c = 0.001$
	Pass loss exponent	$\alpha = 4$
Receiver	Channel estimation	Ideal
	Equalization	MMSE-FDE
Users	Random arrival	Poisson distribution $\lambda = 1 \sim 16$
	Access time duration	1 unit time
	User rates	R, $2R$, $4R$, $8R$
	Rate distribution pattern(P_{8R}, P_{4R}, P_{2R}, P_R)	(0.25, 0.25, 0.25, 0.25)

QPSK, quadrature phase shift keying; FFT, fast Fourier transform; GI, guard interval; MMSE-FDE, minimum mean square error frequency-domain equalization.

Six neighboring cells surrounding the desired cell are considered. The simulation conditions are shown in Table II. To estimate the multi-rate code assignment algorithm, the BER performances of the users who have been successfully assigned a block-level code are evaluated correspondingly. The BS checks if the BER is lower than BER_{req} (the required BER), and then, it is declared that the user is successfully accessed, else the user is blocked.

Users are assigned the codes by the proposed code assignment algorithm described in Section 4. In the following, the BER performance of a user who has been assigned a code is evaluated. Ideal channel estimation is assumed. It also assumed that all necessary information in step 8 or step 9 are available, that is, $SF_{u,f}$, $SF_{u,t}$, and U_{serv} (which have been determined by step 8 or step 9). Figure 9 shows the computer simulation procedure to check if the BER of a user who has been successfully assigned the code is below BER_{req}.

In this paper, we assume the Jakes channel model with 16-path uniform power delay profile (each path consisting of 32 unresolvable paths) and the normalized maximum Doppler frequency of $f_D T_c(N_c + N_g) = 0.001$, where $f_D = \max_{b=0\sim 6, u=0\sim U_b-1}\left(f_D^{b\_u}\right)$ (this corresponds to a moving speed of 60 km/h at 2-GHz carrier frequency for a data rate of 32 Msymbol/s). The most popular channel model is 3GPP Space Channel Model (SCM) or Space Channel Model Extended, which was first proposed in 3GPP TR 25.996 Release 8 and further modified in ETSI TR.125. 996 [26]. In SCM, as it considers six resolvable paths with each consisting of 20 unresolvable paths, it seems to be applicable to the frequency bandwidth narrower than or equal to 5 MHz. Hence, for theoretical analysis, we use more general and tractable Jakes channel model instead of SCM.

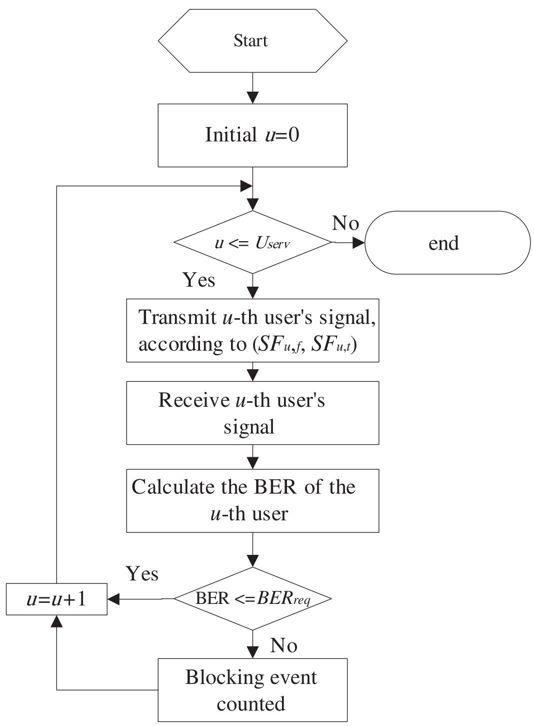

Figure 9. Computer simulation procedure.

5.2. Minimum required distance ratio

First, the relationship between the BER performance and the distance ratio $\Lambda^{-1} = D_{b\_u'(b')} / D_{b'\_u'(b')}$ is discussed. The simulation result is plotted in Figure 10 with the block-level spreading factor $SF_{t\,max}$ as a parameter for $SF_{f\,max} = 16$ and the average bit energy-to-AWGN

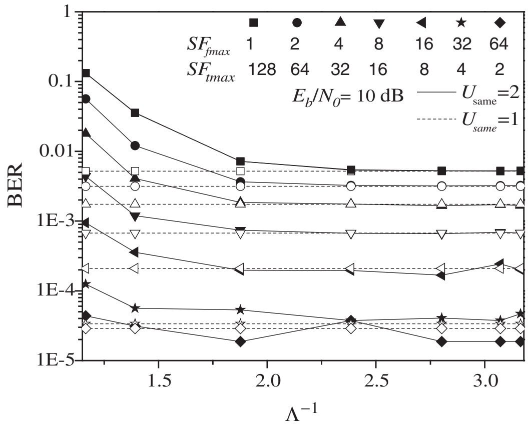

Figure 10. Bit error rate (BER) versus Λ^{-1} with $SF_{\max} = 128$ and $E_b/N_0 = 10$ dB.

power spectrum density ratio $E_b/N_0 = 10$ dB. U_{same} is the number of users who are assigned the same block-level spreading code in different cells ($U_{\text{same}} \leq 7$ for a seven-cell model). From the figure, it is shown that as Λ^{-1} increases the MAI from other users in the other cells who are assigned the same block-level spreading code becomes weaker. When Λ^{-1} is large enough, the MAI is negligibly small, and therefore, almost the same BER as the single-user case can be achieved. It is also seen that as the $SF_{f\,\max}$ increases, the BER reduces significantly; in the single-user case (i.e., $U_{\text{same}} = 1$), the average BER is 5.2×10^{-3} when $SF_{f\,\max} = 1$ and reduces to 2.1×10^{-4} when $SF_{f\,\max} = 16$. The BER difference for different values of U_{same} is very small. When $SF_{f\,\max} = 1$ and $\Lambda^{-1} = 1.88$ (because the BER performance is almost the same for $\Lambda^{-1} \geq 1.88$, $\Lambda^{-1} = 1.88$ is chosen), the BER is $= 7.2 \times 10^{-3}$ when $U_{\text{same}} = 7$, whereas it is 7.1×10^{-3} when $U_{\text{same}} = 2$.

5.3. Code reuse efficiency

The relationship between code reuse efficiency and traffic load is plotted in Figure 11. Traffic load is defined as the average number of new user arrivals per cell during the call duration time. It is seen from Figure 11 that the proposed code reuse algorithm achieves higher code reuse efficiency than the traditional one (which does not consider the code reuse) [6]. The code reuse efficiency improves with the traffic load increasing. It is because more users try to access the system when the traffic load increases, and then, the probability of users in the code reuse area (indicated as circle area in Figure 4) increases. Furthermore, decreasing the value of Λ^{-1} can improve the code reuse efficiency at the expense of increased BER.

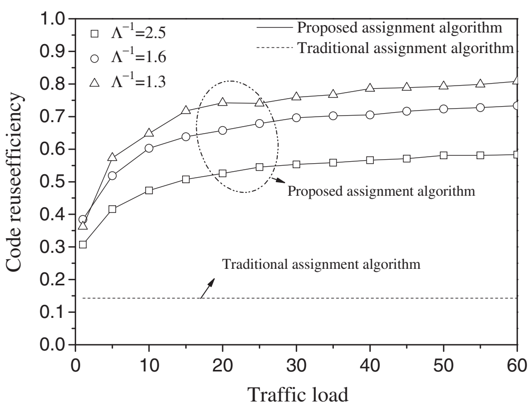

Figure 11. Code reuse efficiency versus traffic load.

5.4. Bit error rate performance

In 2D block spread CDMA, the achievable BER performance depends on the combination of ($SF_{u,f}$, $SF_{u,t}$, $SF_{t\,\max}$, U_b). Below, we discuss the impacts of $SF_{u,f}$, $SF_{u,t}$, $SF_{t\,\max}$, and U_b on the BER performance one by one.

$SF_{u,f}$ is the spreading factor of the chip-level spreading, which obtains the frequency diversity gain. If $SF_{\max}$ and C_u are kept constant, the BER performance improves significantly by increasing $SF_{u,f}$ as shown in Figure 12.

If one of two spreading factors, $SF_{u,f}$ and $SF_{u,t}$, is kept constant while increasing the other spreading factor, the BER performance changes. By increasing $SF_{u,f}$ while keeping $SF_{u,t}$ constant, the BER performance improves significantly. On the other hand, when $SF_{u,f}$ is kept constant, the BER performance stays almost unchanged as shown in Figure 13.

For one-dimension (1D) CDMA, the MAI limits the achievable BER performance. As the number of users increases, the BER performance degrades as shown in Figure 14, whereas 2D block spread CDMA provides a much better BER performance as shown in Figure 15.

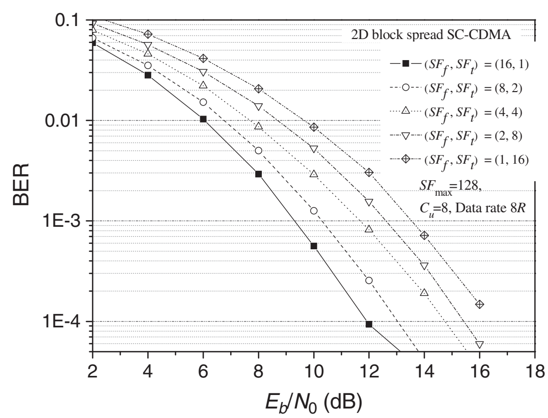

Figure 12. Bit error rate (BER) performance with the $SF_{\max} = 128$ and $C_u = 8$. SC-CDMA, single-carrier code division multiple access.

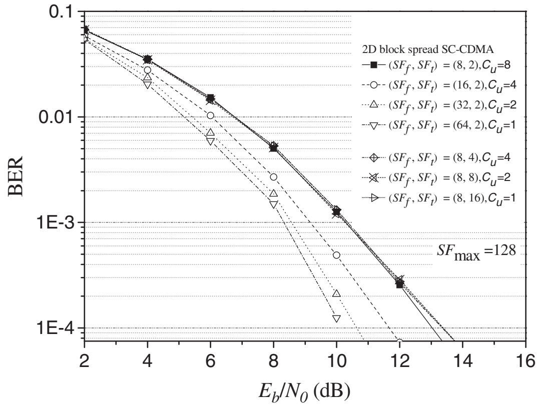

Figure 13. Bit error rate (BER) performance with different data rate as a parameter. SC-CDMA, single-carrier code division multiple access.

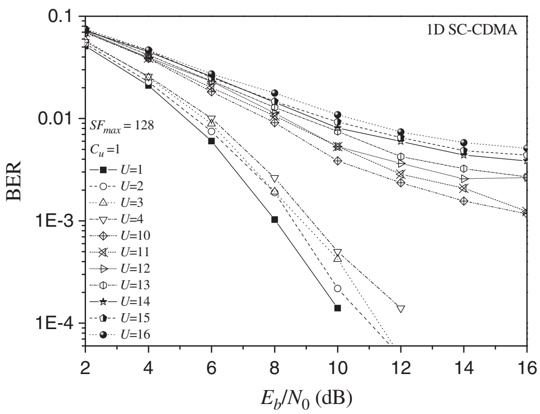

Figure 14. Bit error rate (BER) performance of 1D single-carrier code division multiple access (SC-CDMA) with the number of users as a parameter.

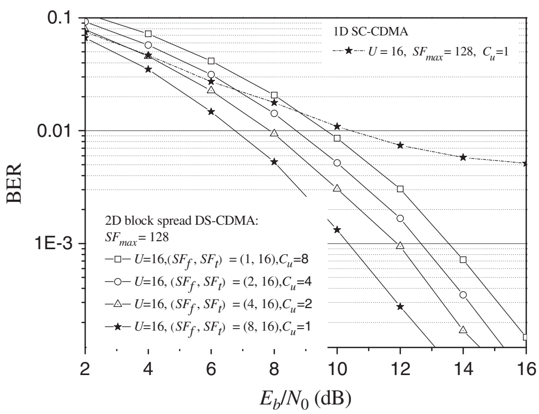

Figure 15. Bit error rate (BER) performance comparison between 2D block spread code division multiple access (CDMA) and 1D CDMA.

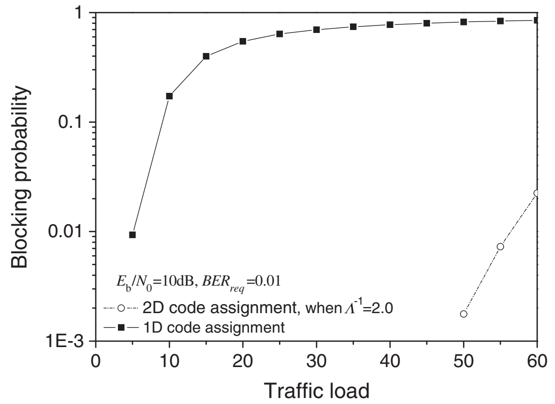

Figure 16. Blocking probability.

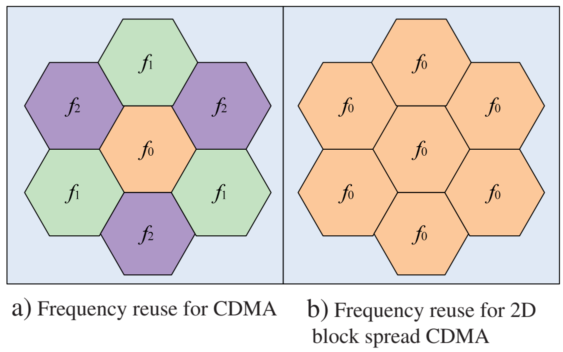

Figure 17. Frequency reuse pattern.

5.5. Blocking probability

Below, $BER_{\text{req}} = 0.01$ is assumed. The BER_{req} influences the blocking probability significantly. The blocking probability increases dramatically with the increasing of BER_{req}. The blocking probability is compared between traditional 1D CDMA and 2D block spread CDMA in Figure 16. From the figure, it can be seen that the blocking probability of 2D block spread CDMA is much lower than that of 1D CDMA because of the lower signal-to-interference plus noise power ratio. In 1D CDMA, different carrier frequencies are used in different cells to avoid the inter-cell MAI [27] (here, we only take the simplest case as an example), as shown in Figure 17. On the other hand, 2D block spread CDMA can use the same carrier frequency in all cells while sufficiently eliminating the inter-cell MAI by block-level spreading, resulting in better frequency efficiency than 1D CDMA.

6. CONCLUSIONS

This paper proposed a code assignment algorithm, considering code reuse scheme, for uplink multi-users/multi-rates 2D block spread multi-cells CDMA. A mathematic interference model was presented, and the required code reuse conditions were discussed so that pair of users was able to share the same block-level spreading code in different cells. By considering both chip-level and block-level spreading codes, a flexible multi-rate for multi-users was possible. The computer simulation results demonstrated that the proposed code assignment algorithm increased the code reuse efficiency significantly while keeping the lower blocking probability compared with the traditional 1D cellular CDMA system.

ACKNOWLEDGEMENTS

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REFERENCES

1. Adachi F. Wireless past and future-evolving mobile communications systems. *Transactions on Fundamentals of Electronics and Communications* 2001; **E84-A**(1): 55–60.
2. Adachi F, Garg D, Takaoka S, Takeda K. Broadband CDMA techniques. *IEEE Wireless Communications* 2005; **12**(2): 8–18.
3. Hanzo L, Munster M, Choi BJ, Keller T. *OFDM and MC-CDMA for Broadband Multi-user Communications, WLANs and Broadcasting*. Wiley: Chichester, 2003.
4. Hara S, Prasad R. Overview of multicarrier CDMA. *IEEE Communications Magazine* 1997; **35**: 126–133.
5. Adachi F, Sao T, Itagaki T. Performance of multicode DS-CDMA using frequency domain equalization in a frequency selective fading channel. *Electronics Letters* 2003; **39**(2): 239–241.
6. Liu L, Adachi F. 2-Dimensional OVSF spread/chip-interleaved CDMA. *IEICE Transactions on Communications* 2006; **E89-B**(12): 3363–3375.
7. Adachi F, Sawahashi M, Okawa K. Tree structured generation of orthogonal spreading codes with different lengths for forward link of DS-CDMA mobile radio. *Electronics Letters* 1997; **33**: 27–28.
8. Saini DS, Bhooshan SV. Adaptive assignment scheme for OVSF codes in WCDMA, In *International Conference on Wireless and Mobile Communications 2006 (ICWMC 2006)*, Bucharest, Romania, 29–31 July 2006; 65–65.
9. Chao CM, Tseng YC, Wang LC. Reducing internal and external fragmentations of OVSF codes in WCDMA systems with multiple codes. *IEEE Transactions on Wireless Communications* 2005; **4**: 1516–1526.
10. Tseng YC, Chao CM, Wu SL. Code placement and replacement strategies for wideband CDMA OVSF code tree management, In *IEEE Globecom 2001*, Vol. 1, San Antonio, Texas, USA, Nov. 2001; 562–566.
11. Saini DS, Bhooshan SV. Assignment and reassignment schemes for OVSF codes in WCDMA, In *International Conference on Wireless and Mobile Communications 2006 (ICWMC 2006)*, Vancouver, Canada, July 2006; 497–502.
12. Chen W-T, Wu Y-P, Hsiao H-C. A novel code assignment scheme for W-CDMA systems, In *IEEE Vehicular Technology Conference 2001 Fall (VTC2001 Fall)*, Vol. 2, Atlantic City, NJ, USA, 7–11 Oct. 2001; 1182–1186.
13. Yang Y, Yum T-SP. Nonrearrangeable compact assignment of orthogonal variable-spreading-factor codes for multi-rate traffic, In *IEEE Vehicular Technology Conference 2001 Fall (VTC2001 Fall)*, Vol. 2, Atlantic City, NJ, USA, 7–11 Oct. 2001; 938–942.
14. Minn T, Siu K-Y. Dynamic assignment of orthogonal variable spreading-factor codes in W-CDMA. *IEEE Journal on Selected Areas in Communications (JSAC)* 2000; **18**(8): 1429–1440.
15. Gong D, Yan Y, Lu J. Dynamic code assignment for OVSF code system, In *IEEE Globecom 2005*, Vol. 5, St. Louis, Missouri, 28 Nov.–2 Dec. 2005; 2865–2869.
16. Assarut R, Kawanishi K, Yamamoto U, Onozato Y, Matsushita M. Region division assignment of orthogonal variable spreading-factor codes in W-CDMA, In *IEEE Vehicular Technology Conference 2001 Fall (VTC2001 Fall)*, Vol. 3, Atlantic City, NJ, USA, 7–11 Oct. 2001; 1884–1888.
17. Sekine Y, Kawanishi K, Yamamoto U, Onozato Y. Hybrid OVSF code assignment scheme in W-CDMA, In *Communications, Computers and signal Processing, 2003. PACRIM. 2003 IEEE Pacific Rim Conference on*, Vol. 1, Japan, Aug. 2003; 384–387.
18. Park J-S, Lee DC. On static and dynamic code assignment policies in the OVSF code tree for CDMA networks, In *IEEE Military Communications Conference (MILCOM 2002)*, Vol. 2, 7–10 Oct. 2002; 785–789.
19. Merani M, Pettenati M. How to veritably determine the accomplishments of static and dynamic OVSF code assignment algorithms, In *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2006)*, Helsinki, Sept. 2006; 1–6.
20. Yu Q, Adachi F, Meng W. Adaptive code assignment algorithm for a multi-user/multi-rate CDMA system. *IEICE Transactions on Communications* 2009; **E92-B**(05): 1600–1607.

21. Yu Q, Meng W, Adachi F. A code assignment algorithm for multi-user/multi-rate 2-Dimensional block spread SC-CDMA, In *Chinacom2011*, Harbin, China, Aug. 2011; 156–160.
22. Wang S, Yu Q, Meng W. Code assignment algorithm for 2-dimensional block spread CDMA uplink in multi-cell system, In *The 2nd International Congress on Image and Signal Processing (CISP2009)*, Tianjing, China, Oct. 2009; 1–5.
23. Rappaport TS, Milstein LB. Effects of path loss and fringe user distribution on CDMA cellular frequency reuse efficiency, In *Global Telecommunications Conference, 1990, and Exhibition. 'Communications: Connecting the Future', GLOBECOM '90, IEEE*, Vol. 1, San Diego, CA, Dec. 1990; 500–506.
24. Wang ZS, Kudoh E, Adachi F. Uplink link capacity of DS-CDMA packet mobile communications with rake combining and transmit power control. *IEICE Transactions on Communications* 2003; **E86-B**(7): 2203–2206.
25. Jakes WC. *Microwave Mobile Communications*. Wiley: New York, 1974.
26. ETSI TR 125 996 V8.0.0 (2009-01). Universal Mobile Telecommunications System (UMTS): spacial channel model for multiple input multiple output (MIMO) simulations. *3GPP TR 25.996 version 8.0.0 Release 8 Technical Report*, Jan. 2009.
27. Ye W, Cui H. Mining of reuse patterns in CDMA network optimization, In *Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing, 2007. SNPD 2007. Eighth ACIS International Conference on*, Vol. 3, Qingdao, China, July 30–Aug. 1 2007; 1011–1016.

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