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Adaptive Code Assignment Algorithm for a Multi-User/Multi-Rate CDMA System

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SUMMARY Code division multiple access (CDMA) technique is used widely since it can flexibly support multi-rate multi-media services by changing the number of orthogonal spreading codes. In this paper, we present a new adaptive code assignment algorithm, which consists of three steps: reserved-space, improved-crowded-first-space, and multi-code combination to fully use the code space. Compared with the existing algorithms, the proposed algorithm can avoid the code blocking problem and lower its total blocking probability while keeping its computational complexity relatively low. Simulation results show that increasing the free space reduces the average total blocking probability while increasing the blocking probability of high rate users.

key words: *code assignment, code tree, cost function, DCA, CDMA*

1. Introduction

In next generation mobile communications, a flexible support of multi-rate/multi-user services is required [1], [2]. Code division multiple access (CDMA) technique is used widely to achieve this through changing the number of orthogonal spreading codes. The well-known CDMA techniques include single-carrier direct sequence DS-CDMA using time-domain spreading [2], [3] and multi-carrier MC-CDMA using frequency-domain spreading [4], [5]. Recently, it was shown that the frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can significantly improve the bit error rate (BER) performance in a severe frequency-selective fading channel [2], [6].

How to deal with the code assignment for multi-rate/multi-user transmission is an important technical problem. It is well-known that higher rate transmission can be achieved by using lower spreading factor in CDMA using orthogonal variable spreading factor (OVSF) codes [8]. When one code is used in the OVSF code tree, its descendant and ancestor codes cannot be used. This is because any two codes belonging to the same mother code are not orthogonal to each other. Therefore, the OVSF code tree has a limited number of available codes [9]. Since the number of OVSF codes is limited, the efficient assignment of OVSF codes has a significant impact on the resource utilization. Every time old users leave and new users arrive, the reassignment of OVSF codes should be efficiently done.

Recently, many researchers have been focusing on the code re-assignment problem. In [10]–[14], various code assignment algorithms, such as random, leftmost, crowded-first-space, crowded-first-code, and nonrearrangeable compact assignment (NCA) algorithms, have been proposed to find an optimum code to be assigned to a new user. In [15], [16], dynamic code assignment (DCA) algorithms to reduce the blocking probability are presented, which are optimal in the sense that the number of OVSF codes that must be reassigned to support a new user is minimized. However, these algorithms are very computationally complex [15]. Recently, less complex algorithms were proposed [17]. These algorithms are a kind of static code assignment algorithms. But, they are not very flexible compared with DCA and provide a relatively high blocking probability since it does not consider the data rate distribution among users. An interesting code assignment algorithm is a hybrid algorithm of dynamic and static algorithms [18]–[20]. However, the proposed hybrid algorithms do not consider how to set the boundary of the code space and assume a fixed user rate distribution only, and furthermore do not describe the proposed algorithms in detail.

This paper proposes a new adaptive code assignment algorithm for a multi-rate/multi-user CDMA system [21]. The remainder of the paper is organized as follows. Section 2 reviews the OVSF code tree and multi-code spreading. Then, the proposed adaptive code assignment algorithm is introduced in Sect. 3. In Sect. 4, the simulation results for the blocking probability are presented and discussed. Finally, Sect. 5 offers some concluding remarks.

2. Preliminary

2.1 OVSF Code Tree

OVSF codes can be represented by a code tree as shown in Fig. 1. Each OVSF code is denoted by $C_{p,k}$, where p represents the code layer and k $(= 0, 1, \ldots, 2^{p-1}-1)$ represents the spreading code index in layer p. The root code is $C_{1,0}=(1)$ and the second layer has two codes, $C_{2,0}=(1, 1)$ and $C_{2,1} = (1, -1)$. The codes at the pth layer are generated as $(C, \overline{C})$ and from each code C of the $(p-1)$th layer, $\overline{C}$ is the bit-wise complement of C [8]. The resulting codes constitute Hadamard Wlash sequences. The number of codes available at the pth layer is 2^{p-1} and is the same as the spreading

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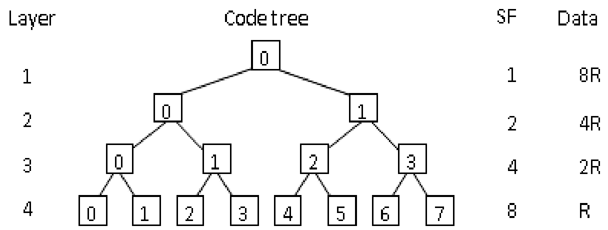


Fig. 1 OVSF code tree.

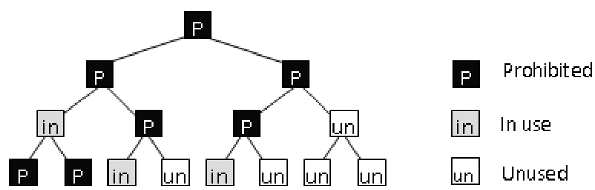


Fig. 2 Code blocking.

factor SF of the layer. All codes in the same layer are orthogonal to each other while codes in different layers are orthogonal only if they do not have the same mother code. The data rate in the highest layer has the lowest rate and is represented by R in this paper.

2.2 Blocking

2.2.1 Total Blocking Probability

Some users cannot be served or blocked because of the capacity limitation of the code tree. All the code assignment algorithms for an OVSF-CDMA system considered the capacity-limitation only. However, blocking can happen not only due to the capacity limitation of the code tree but also due to the insufficient capability of code assignment (this is called the code blocking probability in this paper).

Define the code blocking probability as the probability of a new user being blocked due to the limited capability of code assignment algorithm used even though enough capacity remains. Figure 2 shows a 4-layer code tree with three codes in use, seven codes prohibited, and five codes free. The total capacity of the code tree of Fig. 2 is $8R$. The unused capacity is $4R$. If a coming user requesting the rate $4R$ arrives, theoretically we could serve this user. But, since each used code has either $1R$ or $2R$, this user cannot be served.

In this paper, the total blocking probability is defined as the sum of the blocking probability due to the capacity limitation of the code tree and the code blocking probability due to the insufficient capability of code assignment.

2.2.2 Cost Function

An important metric for assessing the performance of a code reassignment algorithm is its cost function. In [15], the cost of reassigning an occupied code C is defined as the minimum number of code reassignments necessary to make code C and all of its descendant codes free. Since the reassignment of a code of rate R results in no additional code reassignments its cost is 1 by definition. The actual cost depends on the number of reserved codes in the code tree. If any code exists in an immediate higher layer, the cost is only 1.

2.3 Multi-Rate Transmission

Code-multiplexing achieves a flexible rate transmission by using multiple low rate orthogonal codes in parallel. Assume that the requesting rate by a new user is $8R$. Instead of directly using a single spreading code of spreading factor to realize rate $8R$, code-multiplexing can be used. The possible code combinations are ($4R$, $4R$), ($4R$, $2R$, $2R$), ($4R$, $2R$, R, R), ($4R$, R, R, R, R), ($2R$, $2R$, $2R$, $2R$), ($2R$, $2R$, $2R$, R, R), ($2R$, $2R$, R, R, R, R), ($2R$, R, R, R, R, R, R), and (R, R, R, R, R, R, R, R). All of these code combinations give the same sum rate of $8R$.

3. Adaptive Code Assignment Algorithm

The code assignment is declared to be blocked when a user cannot be assigned a code which achieves the requested rate. In order to reduce the code blocking problem, we propose a new adaptive code assignment (ACA) algorithm. The proposed algorithm consists of three steps: reserved-code space (RS) step, improved-crowded-first-space (ICFS) step, and multi-code-combination (MCC) step.

3.1 Overall Algorithm

In the proposed ACA algorithm, the whole code space is partitioned into reserved-code space and free-code space. The capacity ratio of free-code space to whole code space is denoted by the code space partition ratio Q ($0 \leq Q \leq 1$), which is determined by the user data rate distribution.

Proposed ACA algorithm is shown in Fig. 3. Before describing RS, ICFS, and MCC steps in detail, the overall algorithm is briefly described below.

(a) Rank the new users in the ascending order of data rate (low-to-high) according to new users' requested date rates.

(b) Assign a new code to each of new users in RS step. If a code with the data rate requested by the user remains in the reserved-code space, assign this code to the user. Repeat this step for other users. If all of new users are assigned codes successfully, the code assignment procedure stops at this step. Otherwise, go to step (c) for users who have not been assigned codes yet.

(c) Check the available capacity of the free-code space. If an enough capacity remains, carry out the code assignment using ICFS until all of remaining users have been assigned codes successfully. If not, go to step (d).

(d) Assign appropriate codes to the remaining users using MCC. In this step, if the remaining capacity of the free-code space is larger than or equal to the requested sum capacity, the remaining users can be assigned codes success-

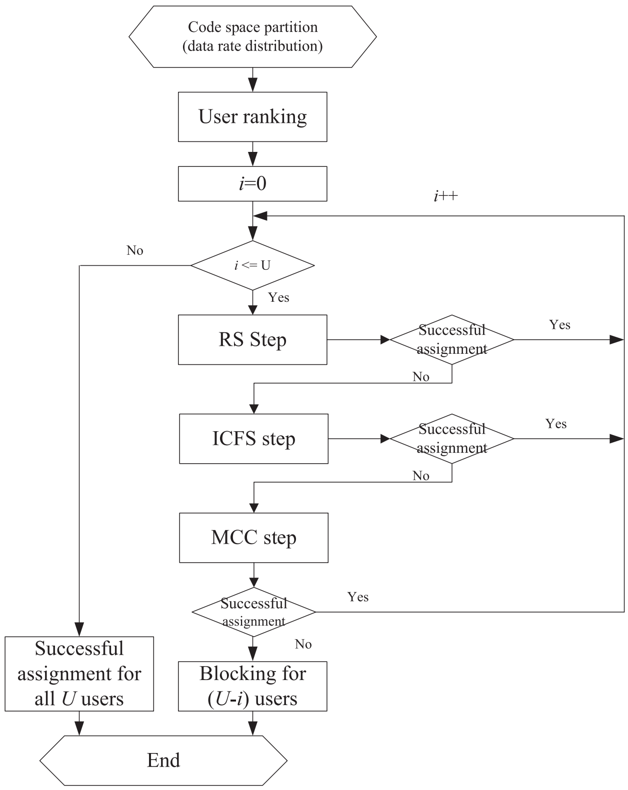


Fig. 3 Proposed ACA algorithm.

fully. If not, the remaining users cannot be assigned codes, resulting in blocking for those users.

3.2 Reserved-Code Space Step (RS)

R is the data rate supported by the highest layer code. The highest layer has C_{SF} codes, where C_{SF} is the capacity of the system and also it is the largest spreading factor. In a code-limited single-cell case, the maximum system capacity normalized by R is equal to C_{SF}. Since all codes are mutually orthogonal, there is no multiple access interference (however, this is only true for the case of down link in a frequency-nonselective channel) [15]. Thus, if the number of users being served is denoted by L and the rate of user i is denoted by k_iR, the following condition should be satisfied.

$$\sum_{i=1}^{L} k_i \leq C_{SF}. \tag{1}$$

The code assignment is carried out while keeping the condition of Eq. (1). Partition the whole code space into two: the reserved-code space and free-code space. Denote the user rate distribution of ($8R$, $4R$, $2R$, R) by (P_{8R}, P_{4R}, P_{2R}, P_R) with

$$P_{8R} + P_{4R} + P_{2R} + P_R = 1. \tag{2}$$

Create a reserved-code space of $(1 - Q)$ times the whole capacity ($0 \leq Q \leq 1$). The number N of supportable users in the reserved-code space is given by

Table 1 Code-space partition.

Layer	Codes in reserved-code space	Codes in free-code space
2 (rate=$8R$)	0	1~3
3 (rate=$4R$)	2	3~7
4 (rate=$2R$)	6	7~15
5 (rate=R)	14	15~31

$$N = \left\lfloor \frac{C_{SF} \times (1 - Q)}{P_{8R}\times 8 + P_{4R}\times 4 + P_{2R}\times 2 + P_R \times 1} + 0.5 \right\rfloor, \tag{3}$$

where $\lfloor x \rfloor$ denotes the largest integer equal to or smaller than x. Therefore, the distribution of supportable users of different rates is given by

$$\begin{cases} N_{8R} = \lfloor N \cdot P_{8R} + 0.5 \rfloor \\ N_{4R} = \lfloor N \cdot P_{4R} + 0.5 \rfloor \\ N_{2R} = \lfloor N \cdot P_{2R} + 0.5 \rfloor \\ N_R = \lfloor N \cdot P_R + 0.5 \rfloor \end{cases}. \tag{4}$$

The reserved-code space capacity is given by

$$\begin{aligned} C_{RS} &= N_{8R} \times 8 + N_{4R} \times 4 + N_{2R} \times 2 + N_R \times 1 \\ &\approx C_{SF} \times (1 - Q). \end{aligned} \tag{5}$$

and the free-code space capacity is given by

$$C_{FS} = C_{SF} - C_{RS} \approx C_{SF} \times Q. \tag{6}$$

Below an example is given to show how the reserved-code space is created. We assume C_{SF}=32 and the user rate distribution of (P_{8R}, P_{4R}, P_{2R}, P_R) = (0.25, 0.25, 0.25, 0.25). When Q=0.5, we have

$$\begin{aligned} N &= \left\lfloor \frac{32 \times (1 - Q)}{0.25\times 8 + 0.25\times 4 + 0.25\times 2 + 0.25\times 1} + 0.5 \right\rfloor \\ &= \left\lfloor \frac{32 \times (1 - 0.5)}{3.75} + 0.5 \right\rfloor = 4 \end{aligned} \tag{7}$$

$$\begin{cases} N_{8R} = \lfloor N \times P_{8R} + 0.5 \rfloor = \lfloor 4 \times 0.25 + 0.5 \rfloor = 1 \\ N_{4R} = \lfloor N \times P_{4R} + 0.5 \rfloor = \lfloor 4 \times 0.25 + 0.5 \rfloor = 1 \\ N_{2R} = \lfloor N \times P_{2R} + 0.5 \rfloor = \lfloor 4 \times 0.25 + 0.5 \rfloor = 1 \\ N_R = \lfloor N \times P_R + 0.5 \rfloor = \lfloor 4 \times 0.25 + 0.5 \rfloor = 1 \end{cases}, \tag{8}$$

and

$$\begin{cases} C_{RS} = N_{8R} \times 8 + N_{4R} \times 4 + N_{2R} \times 2 + N_R \times 1 = 15 \\ C_{FS} = C_{SF} - C_{RS} = 32 - 15 = 17 \end{cases}. \tag{9}$$

An example of the code space partition in each layer is shown in Table 1. Figure 4 illustrates this example. Codes in black color, grey color, and white color represent a reserved code, free code, and prohibited code, respectively.

3.3 Improved-Crowded-First-Space (ICFS) Step

In the reserved-code space, we only need to find an appropriate code according to user's requested data rate. Unlike the RS step, the ICFS step ranks the new users in the ascending (low-to-high) order of requested data rate. A lower rate user is assigned a code first, since the number of lower rate

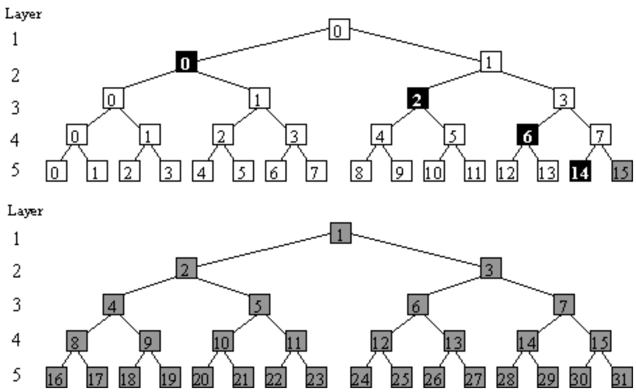


Fig. 4 An example of code-space partition.

codes is larger and consequently to reduce the total blocking probability. This is the difference of the ICFS from the original CFS algorithm [10]. The ICFS step is described below.

(a) Check if the free-code space has enough capacity. If so, go to (b), otherwise go to MCC step.

(b) Pick the candidate code whose ancestor has the least free capacity. The one with least free capacity (i.e., most crowded) will be chosen for use. If two ancestors have the same free capacity, follow the leftmost strategy [10] to pick the code on the left-hand side.

3.4 Multi-Code-Combination (MCC) Step

After carrying out the RS step and ICFS step, if some users with higher rate still do not have been assigned codes, this step is used. If the system has enough remaining capacity to accommodate a user, then assign the multiple codes to meet the requested rate. The reason for carrying out the MCC step last is that the multi-code transmission increases the peak-to-average power ratio (PAPR) of the transmit signal since, in the multi-code transmission, multiple signals spread by different spreading codes are transmitted in parallel, the PAPR increases similar to multicarrier signal transmission [22] and therefore, the average transmit power should be lowered for the given limited peak power.

4. Simulation Results

The performance of the proposed algorithm is evaluated by computer simulation. The maximum *SF* (corresponding to the lowest rate) is set to 128. New users arrive following a Poisson process with average number of arrival users, λ, of 1 to 16. We consider four data rates of R, $2R$, $4R$, and $8R$. User rate distribution patterns considered in the simulation are listed in Table 2. Call duration time is assumed to be exponentially distributed with mean $\mu = 3$ time units. Traffic load G is defined as $G = \lambda \times \mu$.

4.1 Blocking Probability

The code blocking probability of the proposed ACA algorithm is compared with other algorithms in Fig. 5. It can be observed that when the traffic load G is lower than the available capacity, code blocking does not happen with ACA or DCA algorithms. However, code blocking happens if the random or crowded-first space algorithm is used and the blocking probability increases as G increases.

Table 2 Simulation condition.

Maximum *SF*	128
User arrival distribution	Poisson distribution with λ=1~16
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) (0.1, 0.4, 0.4, 0.1) (0.1, 0.1, 0.4, 0.4) (0.4, 0.1, 0.1, 0.4)
Call duration	Exponential distribution with mean μ=3.

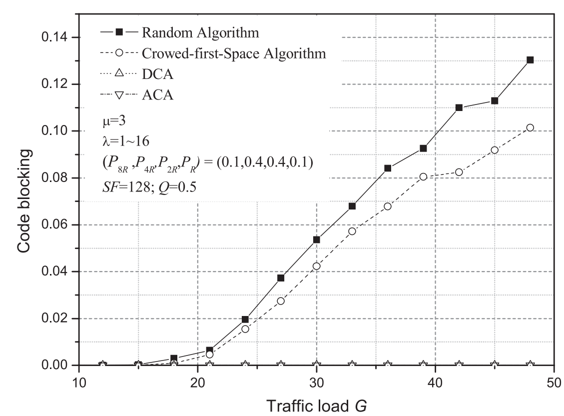


Fig. 5 Code blocking probability.

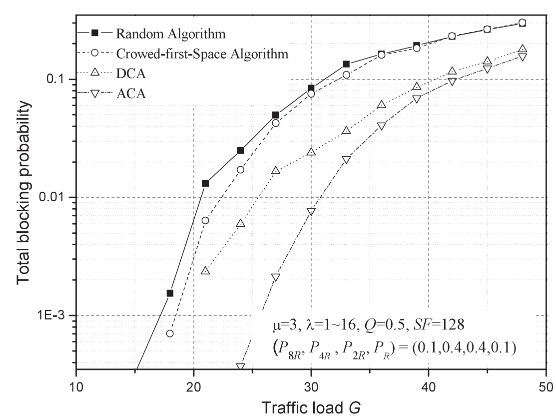


Fig. 6 Total blocking probability.

The total blocking probability of the proposed ACA algorithm is compared with other algorithms in Fig. 6. It is seen that the proposed ACA algorithm outperforms the DCA algorithm and is the best among all algorithms considered here. Why the ACA algorithm provides lower blocking probability than the DCA algorithm is discussed below.

In the DCA algorithm [15], the code to be assigned is searched for from the root code (which provides the highest data rate). Remembering that accommodating a user requesting data rate $8R$ is equivalent to accommodating 8

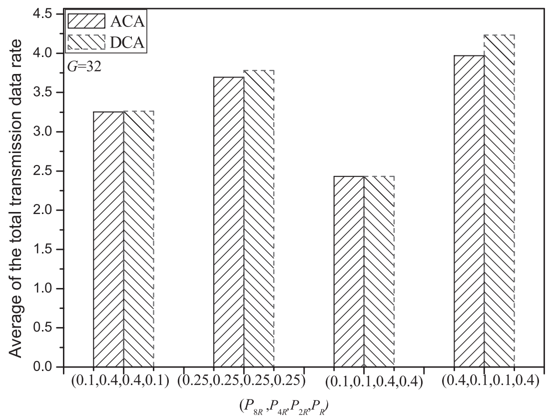


Fig. 7 Comparison of achievable average total rate between ACA and DCA algorithms.

users with data rate R. In the proposed ACA algorithm, users are ranked in the ascending order of rate (i.e., from low-to-high rate). Thus, under the limited capacity of the OVSF code tree, the proposed ACA algorithm provides a lower blocking probability than the DCA algorithm (see Fig. 6) at a slight degradation of the average total rate. This is seen from Fig. 7. It can also be seen from the figure that the achievable average total rate depends on the user rate distribution. The DCA algorithm provides higher total rate than the ACA algorithm, but the difference is small.

If the DCA algorithm applies the user ranking in the ascending order of rate, the blocking probability may become comparable to our proposed ACA algorithm. Such a DCA algorithm first checks if a new user with data rate R_u can be supported, and then, by using an optimal topology search algorithm [15], it searches for the minimum-cost branch whose root code supports the data rate R_u. Here, the minimum-cost branch belongs to the root code which has the least occupied capacity. Once the minimum-cost branch is found and none of its descendant codes is in use, it is assigned to the new user and the process is complete. Otherwise, it is necessary to reassign the descendant codes in use, similar to the code assignment for new users. Thus, if a user with lower rate is assigned first in the DCA algorithm, the number of code reassignment increases significantly and the complexity becomes much higher than the original DCA algorithm.

Complexity is an important factor to compare the different algorithms. For the simplicity purpose, we count the sum of comparison operations and re-code assignment operations. The random algorithm has the lowest complexity, which is given as

$$N_{complex} \approx L \cdot P_{8R} \cdot \frac{SF}{8} + L \cdot P_{4R} \cdot \frac{SF}{4} + L \cdot P_{2R} \cdot \frac{SF}{2} + L \cdot P_R \cdot SF. \quad (10)$$

The complexity of DCA algorithm [15] is given as

$$\begin{aligned} N_{complex} &\approx L \cdot P_{8R} \cdot \left(\frac{SF}{8} \times 2 + \frac{1}{2} \cdot \frac{SF-8}{4} \times 2 + \frac{1}{2} \cdot \frac{SF-8-4}{2} \times 2 + \frac{1}{2} \cdot \frac{SF-8-4-2}{1} \right) \\ &+ L \cdot P_{4R} \cdot \left(\frac{SF}{4} \times 2 + \frac{1}{2} \cdot \frac{SF-4}{2} \times 2 + \frac{1}{2} \cdot \frac{SF-4-2}{1} \right) \\ &+ L \cdot P_{2R} \cdot \left(\frac{SF}{2} \times 2 + \frac{1}{2} \cdot \frac{SF-2}{1} \right) + L \cdot P_R \cdot SF. \end{aligned} \quad (11)$$

Table 3 Complexity comparison.

Algorithm	Random	CFS	DCA	ACA
Complexity	$52.8L$	$92.8L$	$181.7L$	$67.4L$

The complexity of the CFS algorithm [10] is given by

$$N_{complex} \approx L \cdot P_{8R} \cdot \left(\frac{SF}{8} \times 2 \right) + L \cdot P_{4R} \cdot \left(\frac{SF}{4} \times 2 \right) + L \cdot P_{2R} \cdot \left(\frac{SF}{2} \times 2 \right) + L \cdot P_R \cdot SF. \quad (12)$$

Finally, the complexity of the proposed ACA algorithm is given as

$$\begin{aligned} N_{complex} &\approx (1-Q) \cdot (L \cdot P_{8R} \cdot N_{8R} + L \cdot P_{4R} \cdot N_{4R} + L \cdot P_{2R} \cdot N_{2R} + L \cdot P_R \cdot N_R) \\ &+ Q \cdot \left[L \cdot P_{8R} \cdot \left(\frac{SF}{8} \times 2 \right) + L \cdot P_{4R} \cdot \left(\frac{SF}{4} \times 2 \right) + L \cdot P_{2R} \cdot \left(\frac{SF}{2} \times 2 \right) + L \cdot P_R \cdot SF \right] \\ &+ \frac{1}{3} \cdot \left(L \cdot P_{8R} \cdot \frac{SF}{8} + L \cdot P_{4R} \cdot \frac{SF}{4} + L \cdot P_{2R} \cdot \frac{SF}{2} + L \cdot P_R \cdot SF \right). \end{aligned} \quad (13)$$

The complexities of the four algorithms are computed using Eqs. (10)–(13) under the simulation condition shown in Table 2 and the results are listed in Table 3, where L is the number of users being served. It can be seen that the proposed ACA algorithm has a relatively low complexity while achieving better blocking probability performance.

4.2 Impact of Rate Distribution on Total Blocking Probability

How the user rate distribution affects the average total blocking probability of the proposed ACA algorithm is plotted in Fig. 8. It is seen that the more the number of lower-rate users, the lower the total blocking probability. How the total blocking probability differs for a different user rate is shown in Fig. 9. The improvement gained by the lower rate users is more significant, since users with lower rate occupy less code capacity.

4.3 Impact of Q on Total Blocking Probability

Below, we discuss the impact of code space partition ratio

Q, which represents the ratio between reserved space and free space, on the total blocking probability of the proposed ACA algorithm. How Q affects the average total blocking probability and the total blocking probability of a different user rate are shown in Fig. 10 and Fig. 11, respectively.

It can be seen that the average total blocking probability can be reduced as Q increases. However, Q impacts the different rate user differently. It is shown that the reduction in the blocking probability is more significant for the lower rate users (the total blocking probability of users with the lowest rate R reduces to 0 when Q exceeds 0.5). However, with increasing Q, the complexity gets higher as Eq. (13) indicates. Also the total blocking probability for users with higher rate increases. Generally, if the distribution of users with lower rate increases, the code-space partition ratio Q should be increased. With increasing Q, the free space will increase and more number of users with lower rate can be

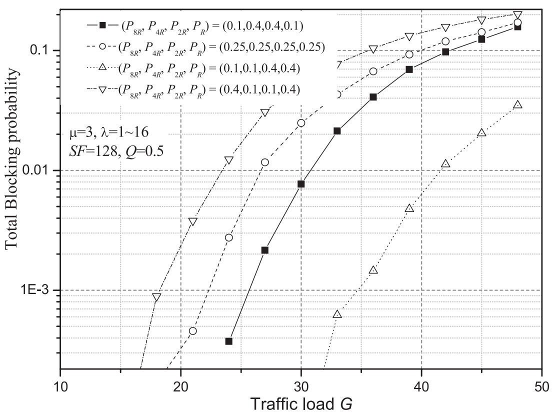


Fig. 8 Impact of user rate distribution on average total blocking probability.

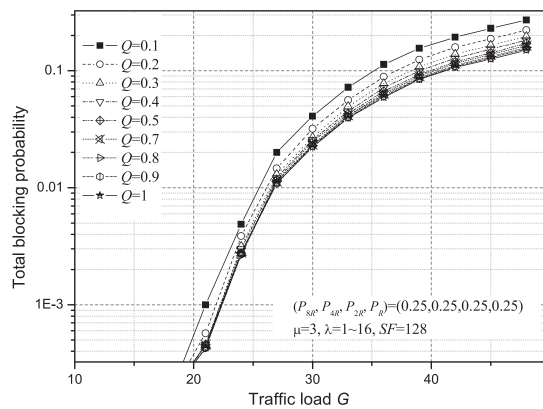
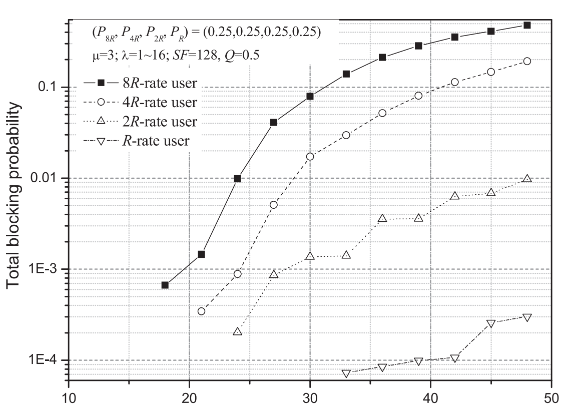
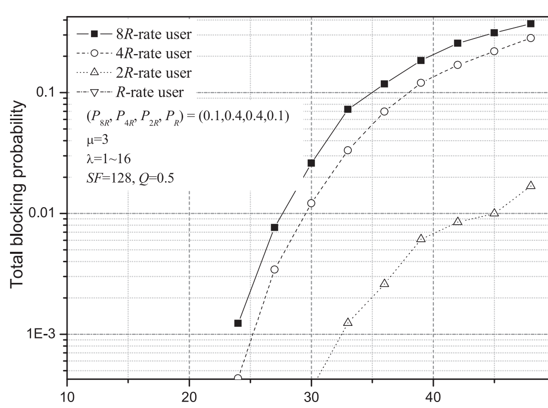


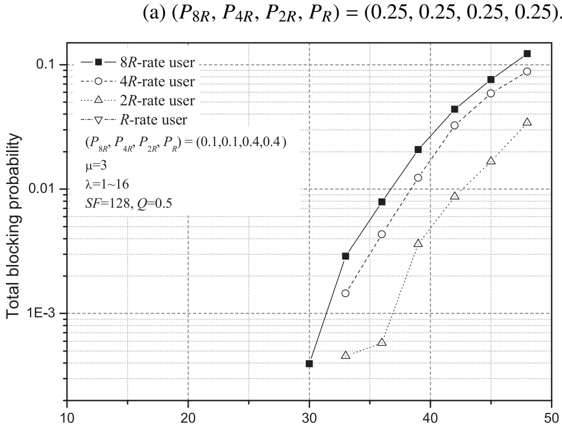
Fig. 10 Impact of Q on average total blocking probability.



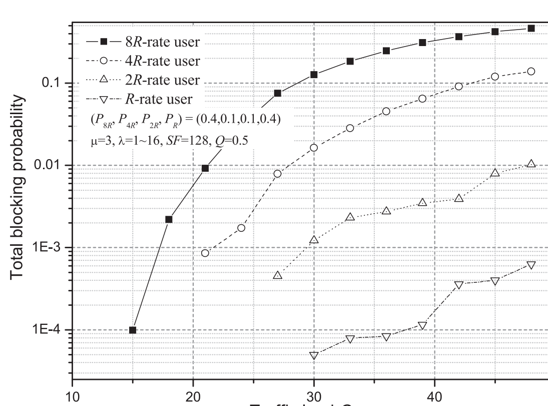
(a) $(P_{8R}, P_{4R}, P_{2R}, P_R) = (0.25, 0.25, 0.25, 0.25)$.



(b) $(P_{8R}, P_{4R}, P_{2R}, P_R) = (0.1, 0.4, 0.4, 0.1)$.

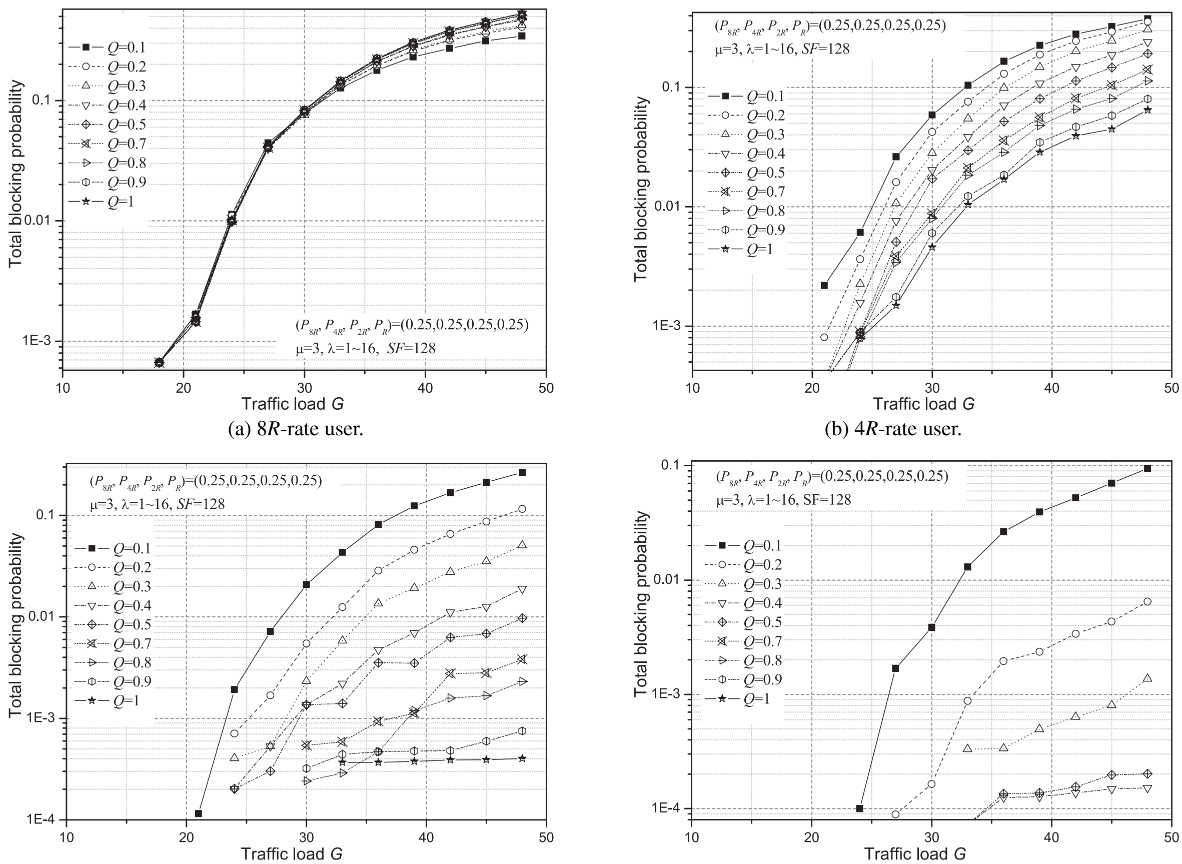


(c) $(P_{8R}, P_{4R}, P_{2R}, P_R) = (0.1, 0.1, 0.4, 0.4)$.



(d) $(P_{8R}, P_{4R}, P_{2R}, P_R) = (0.4, 0.1, 0.1, 0.4)$.

Fig. 9 Blocking probabilities for different user rates.



(a) 8*R*-rate user. (b) 4*R*-rate user. (c) 2*R*-rate user. (d) *R*-rate user.

Fig. 11 Total blocking probabilities of different rate users.

assigned the codes first. Hence, the total blocking probability will decrease.

5. Conclusions

This paper proposed an adaptive code assignment (ACA) algorithm for an OVSF CDMA system. The algorithm performs the code assignment according to *a prior* user rate distribution (which can be obtained by a base station using the statistical traffic analysis). The proposed algorithm consists of three steps: reserved-code space (RS) step, improved-crowded-first-space (ICFS) step, and multi-code-combination (MCC) step. Simulation results have shown that the proposed ACA algorithm can avoid the code blocking problem if the system has enough capacity. Compared with other algorithms, the proposed ACA algorithm achieves smaller total blocking probability while the computation complexity is kept reasonably low. According to the simulation results, if larger free-code space remains, the average blocking probability reduces. However, its complexity increases with the size of free-code space. The blocking probability of high rate users is much higher than lower rate users. If the number of lower rate users increases, the total blocking probability reduces.

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