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Reduction in code blocking using scattered vacant codes for orthogonal variable spreading factor-based wideband code division multiple access networks

Davinder Saini, Neeru Sharma

Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Himachal Pradesh, India
E-mail: davcomm@rediffmail.com

Abstract: 3G and beyond wideband code division multiple access networks use orthogonal variable spreading factor (OVSF) codes to handle multimedia traffic. OVSF codes suffer from the limitation of code blocking, which leads to new call blocking. Scattered vacant codes in the OVSF code tree are the main cause of code blocking. This study proposes compact single code and multicode assignment schemes to reduce code blocking. The vacant codes used for incoming calls are the ones surrounded by a minimum number of consecutive vacant codes. Furthermore, finding consecutive vacant codes at the leaves of the tree is sufficient to find the consecutive vacant codes for all other layers. Handling non-quantised rates with a single code assignment produces wastage of code capacity, which is avoided with the use of a multicode assignment. Multicode usage facility along with the use of vacant codes from the minimum consecutive vacant code groups results in minimum code blocking. Two categories of the multicode assignment schemes are considered: the first one uses the least number of codes and is suitable for rake limited OVSF system, and the second scheme uses maximum number of codes to reduce code blocking significantly.

1 Introduction

Code division multiple access (CDMA) [1, 2] is one of the popular multiple access methods for 3G and beyond wireless networks. In [2], a dynamic frame size adjustment algorithm on the basis of theoretical analysis is described. The preferable length of Gold codes is determined. In current CDMA networks, orthogonal variable spreading factor (OVSF) codes are used to handle variable rate requirements of multimedia traffic. Recently, there has been great interest in the assignment and management of the OVSF code tree at the forward link of the wideband CDMA (WCDMA) wireless interface. OVSF code assignment and management plays an important role in optimising system performance. Most of the work in the literature falls into the dedicated single code class, where the OVSF code is exclusively assigned to one user until the call is terminated (except for the special case of reassignments facility). The code assignment choice depends on the type of input call. In general, the calls can be divided into various categories namely, (i) real-time and non-real-time calls and (ii) quantised and non-quantised calls. Real-time calls are sensitive to delay and jitter. Therefore the number of code searches (which decides call establishment delay) should be small. The non-real-time calls are not delay and jitter sensitive but they need higher rate codes. The quantised rates are those which are in the form of $2^n R$, where n is a positive integer. As the capacity of the OVSF codes is quantised, no wastage occurs at the assignment of codes to such rates. The non-quantised rates, on the other hand suffer from code wastage reducing system performance. When a code tree is used for a sufficiently long time then based on the random call arrival and departure times, the scattering of vacant codes occurs at lower levels (layers), which produces code tree fragmentation [2]. Code scattering predominantly occurs in the lower layers of the code tree [3]. Therefore the improper allocation of codes may lead to heavy code blocking. Good code assignment schemes are the ones that provide minimum code scattering. A large number of schemes exist in the literature which deals with the problems of code tree fragmentation and code blocking.

In this paper, two compact code assignment schemes: one with single code usage and another with multiplecodes usage are described to minimise code blocking. In the single code assignment, for a new incoming call one vacant code is used, which is selected from the maximum scattered vacant code group. This makes the available capacity for future high rate calls maximum. Compared with the single code assignment, the multicode approach reduces code blocking significantly because in this approach multiplecodes can be used in handling one call. Two multicode schemes are proposed in the paper: one for code/rake limited scenario that uses minimum number of codes (rakes), and another for the minimum code blocking scenario that uses maximum number of codes.

The remainder of the paper is organised as follows. Section 2 explains OVSF code tree generation, the code scattering (blocking) problem and the methods to reduce code blocking. Section 3 explains single code and multicode assignment schemes to minimise code scattering. Simulation results are presented in Section 4, and the paper is concluded in Section 5.

2 Review of OVSF CDMA

2.1 OVSF code generation and blocking property

OVSF code tree generation is given in [3], where the codes at different layers have different spreading factors (SFs) giving users the flexibility of transmitting at variable rates. Consider the downlink of a CDMA system with L layers in the code tree ($L = 8$ in WCDMA) with layers 1 and L representing leaf codes and root, respectively. A specific code in layer l is represented by $C_{l,n}$, $1 \leq n \leq 2^{l-1}$. The maximum capacity of the code tree is $2^{L-1}R$ (R is 7.5 kbps for the WCDMA forward link). The SF and data rate handled by the layer l are 2^{L-l} and $2^{l-1}R$, respectively. If the new call is in the form of $2^{l-1}R$, it is called quantised; otherwise it is called non-quantised. The code tree is designed to handle quantised calls. If a particular code is used for the new call, the simultaneous use of its descendants or ancestors is not allowed as they are not orthogonal. The requirement of orthogonal codes for calls does not allow full utilisation of the code tree as there may be a situation when the new call requires capacity less than the available tree capacity but is rejected because of scattering of vacant capacity (codes) in the tree. This limitation called code blocking does not allow full utilisation of tree capacity. To illustrate the effect of code scattering consider a five layer OVSF code tree shown in Fig. 1*a* with maximum capacity 16R. The used capacity of the code tree is 7R (1R + 2R + 4R) corresponding to busy codes $C_{1,1}$, $C_{2,3}$ and $C_{3,3}$. The remaining capacity is 16R–7R = 9R. If the new 8R rate call arrives with the requirement of layer four vacant code, it will be rejected as both the codes in layer 4, namely $C_{4,1}$ and $C_{4,2}$ are blocked. If on the other hand, we have a less scattered code tree shown in Fig. 1*b* with used capacity of 7R, the 8R call can be handled using vacant code $C_{4,2}$. Furthermore, if multicode assignment is allowed the 8R rate call can be handled even with a code tree in Fig. 1*a* using vacant codes $C_{2,2}$, $C_{2,4}$ and $C_{3,4}$ handling capacity fractions 2R, 2R and 4R, respectively.

2.2 Scattered vacant codes

Scattered vacant codes are the ones which lie in the neighbourhood of occupied codes. They are called scattered, because they are located randomly in the code tree because of random arrival and departure times blocking more ancestors which is undesirable for future calls. These scattered vacant codes decrease efficiency and throughput of the OVSF-based CDMA systems. Code scattering can be reduced using three different methods namely, (i) efficient code assignment, (ii) reassignment of ongoing calls and (iii) multiplecodes usage per call. The code assignment reduces code scattering by assigning an optimum code from the set of candidate codes at call arrival. The compact single code assignment scheme proposed in this paper allocates the codes to new calls in such a way that the current congested part of the tree becomes more congested making some area of the tree vacant for future rate calls. This compact assignment is based on the scattering level and elapsed time of the already occupied codes. The design is similar to the crowded first scheme [4] but with a difference that although the crowded first scheme is based on branch wise compactness, our scheme is based on compactness at a specific layer/level. In reassignment schemes, reduction in scattering is obtained at the cost of more overhead and complexity. The probability of reassignment is quite high for low to medium traffic load conditions. The use of multiplecodes for a single call requires multiple rake combiners at base station (BS) and user equipment (UE), which increases system cost and complexity.

2.3 Existing code assignment and reassignment schemes

The code assignment schemes fall into two categories, namely, single code [5, 6] and multicode [7, 8] assignment schemes. Single code assignment schemes use one code to handle incoming calls. The incoming call rate should be quantised to avoid internal fragmentation [2]. The single code assignment schemes are simpler, cost effective and require a single rake combiner at the BS/UE. In the leftmost code assignment (LCA) [4], the code assignment is done from the left of the code tree. In random assignment (RA) [4] the vacant code is picked randomly. Both LCA and RA schemes suffer from the limitation of large code blocking and smaller throughput. The crowded first assignment (CFA) [4] scheme uses that vacant code for a new call whose ancestor(s) have the highest number of busy children codes/capacity. The recursive fewer codes blocked scheme in [9] works on top of CFA, and the optimum code is the one that blocks the least number of vacant parent codes. The tie can be resolved by using multiple layer ancestors. In dynamic code assignment [10], the blocking probability is reduced using reassignments of existing codes to other locations making some codes vacant for new calls. The DCA scheme requires extra information to be transmitted to inform the receiver about code reassignments. The DCA–

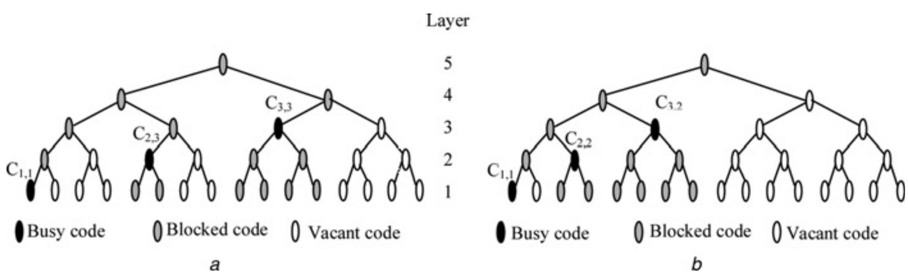

Fig. 1 *Code tree with maximum capacity 16R*

a Scenario I
b Scenario II

CAC scheme [11] reduces the complexity of the DCA scheme for a similar throughput performance. The DCA with multicode combination is investigated in [12], which reduces the number of reassigned codes significantly. Ameco *et al.* [13] discuss a fair single code scheme, reducing weighted code blocking probability. The time based code assignment [14] explains the impact of remaining call service time for reducing code blocking. The multicode assignment schemes use multiple codes in the OVSF code tree and hence multiple rake combiners to handle a single call. Code blocking is reduced significantly compared with single code assignment schemes but the cost and complexity are more. The multicode scheme [2] describes increasing and decreasing strategies (to assign codes from lower to higher layers and vice versa) as well as unified and separated strategies (to use multicode close to or away from each other) to optimise the performance of the multicode approach. The multi rate multicode compact assignment (MMCA) [15] scheme uses the concept of a compact index to accommodate users with varying quality of service (QoS) requirements. The optimum number of codes/rakes to handle quantised and non-quantised calls is formulated in [16]. In code reservation assignment scheme [17], if a code is given to an incoming call, the immediate sibling and all its children are given priority over all the existing vacant codes. For future incoming calls, the vacant code with highest priority is given to the new call. The basic idea is to put all the incoming calls, which come at nearly the same time closest to each other. This almost guarantees that the calls will be terminated at almost the same time and the large capacity portion isvacated. A novel multicode design to reduce code wastage is proposed in [18]. Code wastage is reduced significantly by increasing the number of rakes. The design identifies the optimum number of rakes required for the incoming call. The paper of Kumar and Chellappan [19] is regarding the significance of good resource allocation in 4 G networks. In this paper, the optimal algorithm to manage the resource allocation like bandwidth is described to maximise system performance. The effect of an asymmetric slot management strategy employing adaptive resources in multicarrier code division multiple access (MCCDMA) is discussed. According to the level of traffic, the cell has its own slot allocation policy. In [20], the graph model is used to define optimality for code assignment. The design is optimal if it meets the current request and ensures that the remaining capacity is broken into the least number of fragments. A novel graph model, called constrained independent domination problem (CIDP) is created for code assignment and is proved to be NP complete for general graphs. The CIDP graphs reduced from the OVSF code assignment problem belong to trivial perfect graphs. The optimum number of codes/rakes to handle quantised and non-quantised calls is formulated in [21].

3 Compact code assignments

3.1 Single code assignment

At a specific time instant the busy codes and vacant codes are known in the code tree. A code $C_{l,n}$ is part of a group with $b = 2^{l'}$, $(l' < l)$ consecutive vacant codes if the following is true.

Condition 1: Code $C_{l+l',\lceil n/2^{l'}\rceil}$ and all its children in layer l are vacant.
Condition 2: Code $C_{l+l'+1,\lceil n/2^{l'+1}\rceil}$ is blocked.

Let scattering index $N_{l,b}$ denote the number of codes in layer l within a group of b consecutive vacant codes whose ancestors in layers $l + \log_2(b)$ to L are same. For a new quantised call $2^{l-1}R$ the design identifies the vacant code $C_{l,n}$ in layer l that is within the group $N_{l,b}$ vacant code group, where $b = \min(1, 2^{l-1})|N_{l,b} \neq 0$, that is, the code with the minimum consecutive vacant codes is the candidate for handling a new call with rate $2^{l-1}R$. The index $N_{l,b}$ is a measure of scattering in the OVSF code tree. The use of a vacant code from the optimum $N_{l,b}$ group guarantees code usage from the most congested portion. This makes the future high rate calls handling probability maximum. If $N_{l,b}$ is known for layer l, it can be shown that for a layer l'

$$N_{l+l',b/2^{l'}} = N_{l,b}, \quad \text{for } l' \leq L - l \tag{1}$$

Therefore it is sufficient to find the scattering index in layer 1, that is, $N_{1,b}$ as higher layer indices can be derived from it. The relationship between $N_{l,b}$ and $N_{l,b}$, $l \in [2, L]$ is given in Table 1 for the WCDMA system with eight layers. Also, as the multiple candidate codes are available in the optimum vacant code group, the most appropriate vacant code can be found by the elapsed time information of busy neighbour of codes within the minimum consecutive vacant group. For a vacant code $C_{l,n}$ in group $N_{l,b}$, define neighbour codes as those codes in the layer l, which are the children of the code $C_{l+\log(b),\lceil l/2^{\log(b)}\rceil}$. Find the number of busy children of the code $C_{l+\log(2b),\lceil n/2^{\log(b)+1}\rceil}$ (say N). For all N busy codes, find the average elapsed time $\sum_{i=1}^{N} t_i/N$, where t_i represents the elapsed time of the call handled by the ith busy code. Repeat the procedure for all the codes in the group $N_{l,b}$. The children of the parent code of $C_{l,n}$ with minimum average elapsed time will be used for handling a new call. Hence, the code whose sibling(s) have the latest arrival will be used so that all these codes become vacant at the same time. Therefore the crowded portion remains crowded increasing code utilisation and better handling of high rate calls. To illustrate the code assignment scheme, consider a seven-layer code tree in Fig. 2. The consecutive vacant codes groups are given in Table 2. If a $2R$ user arrives, the

Table 1 Deriving consecutive vacant codes groups in layer 2–8 from consecutive vacant codes groups in layer 1

Layer (l) $l = 1$	2	3	4	5	6	7	8
$N_{1,1}$	$N_{2,1} = N_{1,2}$	$N_{3,1} = N_{1,4}$	$N_{4,1} = N_{1,8}$	$N_{5,1} = N_{1,16}$	$N_{6,1} = N_{1,32}$	$N_{7,1} = N_{1,64}$	$N_{8,1} = N_{1,128}$
$N_{1,2}$	$N_{2,2} = N_{1,4}$	$N_{3,2} = N_{1,8}$	$N_{4,2} = N_{1,16}$	$N_{5,2} = N_{1,32}$	$N_{6,2} = N_{1,64}$	$N_{7,2} = N_{1,128}$	
$N_{1,4}$	$N_{2,4} = N_{1,8}$	$N_{3,4} = N_{1,16}$	$N_{4,4} = N_{1,32}$	$N_{5,4} = N_{1,64}$	$N_{6,4} = N_{1,128}$		
$N_{1,8}$	$N_{2,8} = N_{1,16}$	$N_{3,8} = N_{1,32}$	$N_{4,8} = N_{1,64}$	$N_{5,8} = N_{1,128}$			
$N_{1,16}$	$N_{2,16} = N_{1,32}$	$N_{3,16} = N_{1,64}$	$N_{4,16} = N_{1,128}$				
$N_{1,32}$	$N_{2,32} = N_{1,64}$	$N_{3,32} = N_{1,128}$					
$N_{1,64}$	$N_{2,64} = N_{1,128}$						
$N_{1,128}$							

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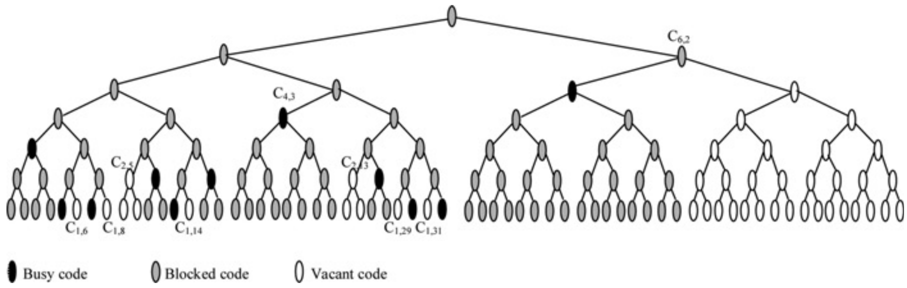

Fig. 2 *Illustration of the single code and multicode assignment scheme for handling quantised and non-quantised data rates*

Table 2 Listing codes in Fig. 2 into groups according to number of consecutive vacant codes

Layer (l)	Codes in group $N_{l,1}$	Codes in group $N_{l,2}$	Codes in group $N_{l,4}$	Codes in group $N_{l,8}$	Codes in group $N_{l,16}$	Codes in group $N_{l,32}$	Codes in group $N_{l,64}$
1	$C_{1,6}$, $C_{1,8}$, $C_{1,14}$, $C_{1,29}$, $C_{2,31}$	$C_{1,9}$, $C_{1,10}$, $C_{1,25}$, $C_{1,26}$	0	0	$C_{1,49}$, …, $C_{1,64}$	0	0
2	$C_{2,5}$, $C_{2,13}$	0	0	$C_{2,25}$, …, C_{232}	0	0	not allowed
3	0	0	$C_{3,13}$,…,$C_{3,16}$	0	0	not allowed	not allowed
4	0	$C_{4,7}$, $C_{4,8}$	0	0	not allowed	not allowed	not allowed
5	$C_{5,4}$	0	0	not allowed	not allowed	not allowed	not allowed
6	0	0	not allowed	not allowed	not allowed	not allowed	not allowed
7	0	not allowed	not allowed	not allowed	not allowed	not allowed	not allowed

vacant code from layer 2 is required. The vacant codes availability is with groups $N_{2,1}$ and $N_{2,8}$. The assignment scheme picks any one code from the group $N_{2,1}$ (either code $C_{2,5}$ or code $C_{2,13}$). Furthermore, the new calls with rates $32R$ and $64R$ will not be handled because of the absence of vacant codes.

For a new non-quantised call kR, $k \neq 2^{l-1}$, there is no code with code capacity kR in the OVSF tree. The optimum code lies in the layer $l'+1$, $l' = \min(l'')|k \leq 2^{l''}$. The code wastage capacity is given by

$$WC = (2^{l'} - k)R \tag{2}$$

For k close to 2^{l-1}, the single code assignment produces large wastage capacity and hence multicode assignment is to be used to avoid this wastage.

3.2 Multicode assignment

The unused capacity in lth layer of the code tree (say A_l) can be defined as

$$A_l = \sum_{i=1}^{l} N_{l,2^{i-1}} \times 2^{i-1}R \tag{3}$$

If on arrival of the new call with rate $2^{l-1}R$ there is no vacant code in layer l, and $A_l \geq 2^{l-1}R$, the single code assignment fails and the call can be handled only with multiplecodes. There are two ways to handle a call with multiplecodes: (i) use of minimum codes and (ii) use of maximum codes.

3.2.1 Call handling with minimum number of codes: On the arrival of quantised call $2^{l-1}R$ in an m rake system, there are two possibilities to handle a new call, (i) $l \leq m$, in this case the codes with capacities 2^iR, $i \in [0, l-1]$ are used, (ii) $l > m$ where the codes with capacities 2^iR, $i \in [l-m, l-1]$ are eligible candidates. The codes assignment is done using successive capacity reduction as follows. Let p_{l-i} be the number of vacant codes in layer $l-i$ to handle full/partial $2^{l-1}R$ call capacity. Also, let P_{l-i}, $\max(P_{l-i}) = 2^{i-1}$ represent layer $l-i$ codes used to handle full/partial call capacity. Starting with layer l the fraction of call capacity handled upto layer $l-x$ is $\sum_{i=0}^{x} P_{l-i} \times 2^{l-i}R$, and layer $l-x$ needs to be checked if, $\sum_{i=0}^{x-1} P_{l-i} < m$. The remaining capacity to be handled by layers 1 to $x-1$ (say Q_{x-1}) is

$$Q_{x-1} = \left(2^{l-1} - \sum_{i=0}^{x} P_{l-i} \times 2^{l-i}\right)R \tag{4}$$

Furthermore, the codes used in different layers should be the ones that belong to minimum consecutive vacant code groups. For a layer $l-i$, if there are j consecutive vacant code groups N_{l-i,a_k}, $k \in [1, j]$ and $a_k = 2^k | 2^k \leq 2^{L-1+i}$, P_{l-i} number of codes in layer $l-i$ should be used from the consecutive vacant code group $N_{l-i,a_{k_1}}$ where $a_{k_1} = \min(a_k)$. If $P_{l-i} > N_{l-i,a_{k_1}}$, some vacant codes are required from second optimum consecutive vacant codes group $N_{l-i,a_{k_2}}$ where $a_{k_2} = \min(a_k)$ and $a_{k_2} > a_{k_1}$. The procedure is repeated for maximum P_{l-i} steps. For any layer $l-i$, the relationship of number of codes, capacity handled and remaining capacity are given in Table 3.

Table 3 Relationship between number of codes, capacity handled, and remaining capacity for new call $2^{l-1}R$ in various layers

Layer ($l-1$) $i = [0,..,l]$	Number of codes used (P_{l-i})	Capacity handled by layers $l-i$	Capacity handled by layers 1 to $l-i-1$
l	0,1	$P_l \times 2^{l-1}$	$2n - P_l \times 2^{l-1}$
$l-1$	0,1,2	$P_{l-1} \times 2^{l-2}$	$2^n - \sum_{i=0}^{1} P_{l-1} \times 2^{l-(i+1)}$
$l-2$	0,1,2,3,4	$P_{l-2} \times 2^{l-3}$	$2^n - \sum_{i=0}^{1} P_{l-i} \times 2^{l-(i+1)}$
….	….	….	….
1	0,1,2,…,2^{l-1}	P_1	Nil

The non-quantised rates in the form of k_1R, $k_1 \neq 2^{l-1}$ (k_1R is used instead of kR for uniform notation) are converted to quantised as follows. Find $\min(l_1)|k_1 \geq 2^{l_1}R$. Calculate $k_2 = k_1 - 2^{l_1}$. Starting with l_1 and k_2, the procedure can be extended to find $\min(l_i)|k_i \geq 2^{l_i}R$ and $k_{i+1} = k_i - 2^{l_i}$ till $k_{i+1} = 2^n$. The quantised rates $2^{l_1}R, 2^{l_2}R, \ldots, 2^{l_{i+1}}R$ are handled as discussed earlier. Assume that the number of rakes required to handle rate components $2^{l_1}R, 2^{l_2}R, \ldots, 2^{l_{i+1}}R$ are $m_1, m_2, \ldots, m_{i+1}$. The new call can be handled only if $\sum_{j=1}^{i+1} m_j \leq m$. The algorithm of the design is given as Fig. 3

3.2.2 Call handling with maximum number of codes: On the arrival of new call $2^{l-1}R$ in m rakes system the essential requirements to reduce code blocking are

- Maximum number of rakes should be utilised.
- Maximum low rate codes should be used.
- Each code selected in the multicode, is used from the consecutive vacant code group $N_{l,b}$ with minimum possible b.

For a new quantised call $2^{l-1}R$, if $2^{l-1}R \leq A_1$ and $m < 2^{l-1}$, the code tree has enough capacity to handle a new call. There are two possibilities: (i) $l > m$ and (ii) $l \leq m$

i. If $l > m$, the codes with capacities $2^{l-i}R$, $i \in [1, m]$ are the candidates to handle a new call. Construct a vector $\boldsymbol{Z} = [z_1, z_2, \ldots, z_m]$, where z_i represents the capacity fraction handled by ith rake in units of R kbps. Initially put the value of each coefficient in Z is equal to 2^{l-m}. Define B_1 as

$$B_1 = 2^{l-1} - (m-1)2^{l-m} \qquad (5)$$

For integer P_1, find $p_1 = \max(P_1)|2^{P_1} \leq B_1$. In vector $\boldsymbol{Z}$, coefficient z_1 is assigned the value equal to 2^{p_1}. The vector $\boldsymbol{Z}$ becomes $Z = \left[2^{p_1}, 2^{l-m}, \ldots, 2^{l-m}\right]$. For $2 \leq i \leq m-2$, calculate $B_i = 2^{p_{i-1}} - (m-i)2^{l-m}$ and $z_i = 2^{p_i}$ and $p_i = \max(P_i)|2^{P_i} \leq B_i$. The vector $\boldsymbol{Z}$ is redefined as $\boldsymbol{Z} = \left[2^{p_1}, 2^{p_2}, \ldots, 2^{p_{m-2}}, 2^{l-m}, 2^{l-m}\right]$. Therefore in maximum code scattering design, one code is used from each of the layer $l-1$, $l-2$, …, $l-(m-2)$ and two codes are used from the layer $l-(m-1)$, and no vacant code is used from layers $l-m$ to 1. Furthermore, the vacant codes in each layer should be used from the least consecutive vacant code group(s).

ii. For $l \leq m$, the codes with capacities 2^iR, $0 \leq i \leq l-1$ are the candidates to handle a new call. Considering $Z = [z_1, z_2, \ldots, z_m]$, find all j, $1 \leq j \leq m-2$ for which $(2^{l-1} - \sum_{i=1}^{j} a_j) > m - j$ where $a_j = 2^{l-1}/2^j$. The vector $\boldsymbol{Z}$ becomes $\boldsymbol{Z} = \leq[2^{l-1}/2, 2^{l-1}/2^1, \ldots, 2^{l-1}/2^j, z_{j+1}, \ldots, z_m]$. Find j, $j = \min[1, m-2]$ for which $2^{l-1} - \sum_{i=1}^{j} a_i = m - j$, where a_i is in the form of 2^n, $n \in [0, l-2]$. The coefficient z_i in vector $\boldsymbol{Z}$ becomes

$$z_i = \begin{cases} a_i, & i = 1, \ldots, j \\ 1, & i = j+1, \ldots, m \end{cases} \qquad (6)$$

The vector z_i represents the capacity fraction handled by the ith rake.

If $m \geq 2^{l-1}$, maximum 2^{l-1} codes of rate R are used to handle a new call. The non-quantised rates are converted into quantised rates as discussed earlier. The algorithm of the design is given as Fig. 4.

To illustrate the multicode assignment scheme consider the seven-layer tree of Fig. 2 assuming that the system is

1. *Rejected calls=0;*
2. *Enter input parameters like user rate kR, number of rakes 'm', number of layers 'L' etc.*
3. *If (rate is quantised, i.e. kR=$2^{l-1}R$)*

    3.1 Find the number of codes required (P_i), $1 \leq i \leq l-1$, total codes available(p_i)

    3.2 Use the vacant codes P_i in layer l-i from least consecutive vacant code groups

    3.3 Go to step 2

  Else

    3.1 Convert non quantised rate into quantised rate fractions $2^{l_1}R, 2^{l_2}R, \ldots 2^{l_{i+1}}R$ requiring rakes $m_1, m_2, \ldots m_{i+1}$.

    3.2 If $\sum_{j=1}^{i+1} m_j \leq m$

      3.2.1 Use codes from layers l_1-1, l_2-1,…l_i to handle new call. All the codes must be from the minimum consecutive vacant code group.

    Else

      3.2.1 Rejected calls=Rejected calls+1

    End

    3.3 Go to step 2

  End

Fig. 3 *Algorithm of the design*

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1. *Rejected calls=0;*
2. *Enter input parameters like user rate kR, number of rakes 'm', number of layers 'L' etc.*
3. *If (rate is quantised, i.e. $kR=2^{l-1}R$)*

   3.1 If $m<2^{l-1}$

   3.1.1 If l>m

   3.1.1.1 Construct vector $Z=[z_1,z_2,.....z_m]$, where $z_i=2^{p_i}$

   3.1.1.2 For rate fraction 2^i, $i\in[1,m]$, assign codes from minimum consecutive vacant group

   Else

   3.1.1.1 Construct $Z=[z_1,z_2,.....z_m]=[2^{l-1}/2,\ 2^{l-1}/2^1,\ 2^{l-1}/2^2,\ldots,\ 2^{l-1}/2^j,z_{j+1},\ldots.,z_{j+1}]$, where $z_i=2^{p_i}$

   3.1.1.2 Assign codes from minimum consecutive vacant group

   End

   Else

   3.1.1 Use m codes of rate R to handle the call

   End

   3.2 Go to step 2

Else

   3.1 Convert non quantised rate into quantised fractions $2^{l_1},2^{l_2},....2^{l_{i+1}}$ requiring rakes m_1, m_2,..m_{i+1}.

   3.2 If $\sum_{j=1}^{i+1} m_j \le m$

   3.2.1 For each m_i use step 3.

   Else

   3.2.1 Rejected calls=Rejected calls+1

   End

   3.3 Go to step 2

End

Fig. 4 *Algorithm of the design*

equipped with four rakes. If a new call with rate $16R$ arrives, that is, l is equal to 5, and $l>m$, for use of maximum scattered codes, the initial value assigned to the four rakes are $\boldsymbol{Z}=[2, 2, 2, 2]$. As per Section 3.2.2 (i), the value of p_1, p_2, p_3 and p_4 becomes 3, 2, 1 and 1, respectively. The vector $\boldsymbol{Z}$ becomes [8, 4, 2, 2] and the codes $C_{4,7}$, $C_{3,15}$, $C_{2,5}$ and $C_{2,13}$ are used to handle capacity portion $8R$, $4R$, $2R$ and $2R$, respectively. If instead of 16R, the new call of rate $8R$ arrives, that is, $l=4$, then as $l\le m$ and $2^{l-1}>m$, the vector $\boldsymbol{Z}$ becomes [4, 2, 1, 1] as per Section 3.2.2 (ii). The codes used are $C_{3,13}$, $C_{2,5}$, $C_{1,6}$ and $C_{1,8}$, respectively. In the above two examples, the effect of elapsed time of busy siblings is not considered, otherwise the selected code may be different.

4 Simulation and results

For simulation, eight-layer OVSF code tree (as per WCDMA specifications) is considered. Only quantised rates $2^{l-1}R$, $l\in[1, 8]$ are considered with rates R, $2R$, $4R$ and $8R$ are treated as real-time calls and rates $16R$, $32R$, $64R$ and $128R$ are treated as non-real time (best effort calls). Let λ_l, ($l\in[1, 8]$) be the arrival rate of 2^lR calls. The total arrival rate of the system is $\lambda=\sum_{l=1}^{8}\lambda_l$. The service time is assumed to be exponentially distributed with average value $1/\mu$ (service rate for all classes is assumed to be same or equal to μ). For simulation, total traffic load ρ (equal to λ/μ) is varied from 1 to 128 calls per unit of time. The arrival rate is assumed to be varying between 1 and 128 calls per unit of time and service time is assumed to be 1 unit of time and service time is 3 units of time. In the single code assignment if rate kR, $2^{l-2}<k\le 2^{l-1}$, arrives the vacant code is required from layer l. Also, the current lth layer λ_l is updated as

$$\lambda_l=\lambda_l+1 \tag{7}$$

In multicode assignment with m rakes, if rate k_1R, $2^{l-2}<k_1\le 2^{l-1}$ arrives, finds k_2, k_3, …, k_{m+1} as in Section 3.2.1. If within m steps, $\sum_{j=2}^{p}k_j=k|p\le m+1$, use of least codes

will update the $\lambda_{l-1}, \lambda_{l-2}, \ldots, \lambda_{l-1}$ to a value given by

$$\begin{aligned} \lambda_{l-1}, \lambda_{l-2}, \ldots, \lambda_{l-m} &= \lambda_{l-1} + a_1 \\ \lambda_{l-2} + a_2, \ldots, \lambda_{l-m} + a_m \end{aligned} \tag{8}$$

In (7) the coefficient a_j, $1 \le j \le m$ can take values 0 or 1. The value of a_j is 0 if k_j is 0 else a_j is 1.

If the multicode assignment with minimum future scattering is used, the codes within the minimum consecutive vacant codes in each layer are picked. If the vector $\boldsymbol{Z} = [z_1, z_2, \ldots, z_t]$, $t \le m$, is calculated as per Section 3.2.2, find $l_i = \log_2(z_i) + 1$ for each z_i. The arrival rate is updated as

$$\lambda_{l_i} = \lambda_{l_i} + 1, \quad 1 \le i \le t \tag{9}$$

Also, for an eight-layer code tree the number of servers (codes) in layer l are $G_l = 2^{8-l}$, $l = [1, 2, \ldots, 8]$. The total codes (servers) in the system assuming eight set of classes are represented by vector $\boldsymbol{G} = [G_1, G_2, G_3, G_4, G_5, G_6, G_7, G_8]$. Also, the maximum number of servers used per call is equal to the number of rakes 'm'. If the traffic load for the

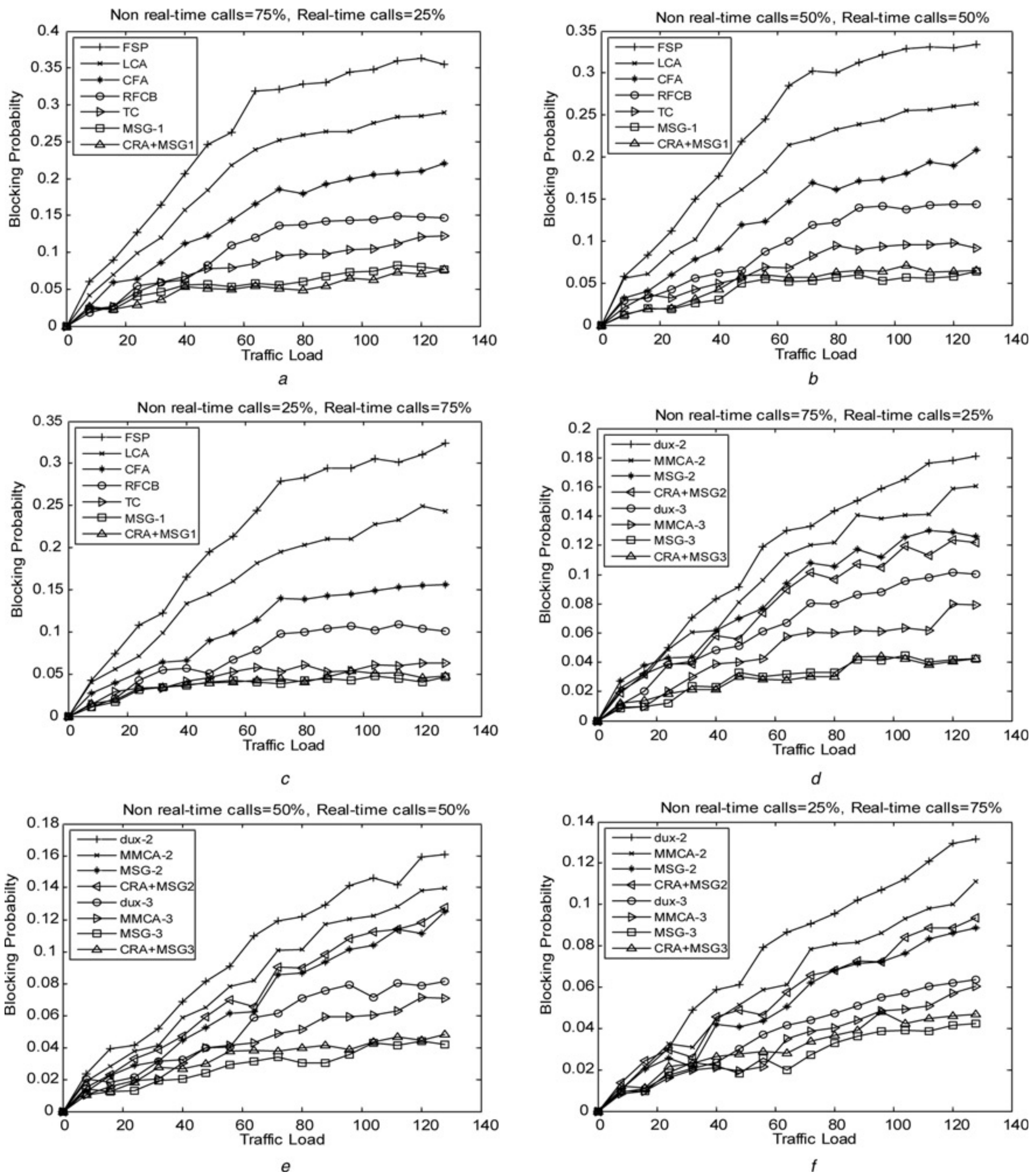

Fig. 5 *Comparison of code blocking for single code and multicode assignment scheme*

a Single code assignment, more non-real-time calls
b Single code assignment uniform distribution
c Single code assignment, more real-time calls
d Multicode assignment, more non-real-time calls
e Multicode assignment, uniform distribution
f Multicode assignment, more real-time calls

lth class is denoted by $\rho_l = \lambda_l/\mu$, and the average traffic load is given by $\rho = \sum_{l=1}^{8} \rho_l$. Code blocking for the lth class is defined by

$$P_{B_l} = \frac{\rho_l^{G_l}/G_l!}{\sum_{n=1}^{G_l} \rho_l^n/n!} \quad (10)$$

The average code blocking for the eight class system is

$$P_B = \sum_{l=1}^{8} (\lambda_l/\lambda) P_{B_l} \quad (11)$$

Let the arrival distribution for the eight classes be given by $[p_1, p_2]$, where p_1 and p_2 are the probabilities of arrival of real time and non-real-time calls. Three arrival distributions are considered as given below

- [0.75, 0.25], real-time calls dominate the traffic.
- [0.5, 0.5], uniform distribution of real time and non-real-time calls.
- [0.25, 0.75], non-real-time calls dominate the traffic.

The single code assignment blocking comparison for the proposed maximum scattered group (MSG-1, and 1 indicates single code facility for the new call) is done with a fixed set partitioning scheme [4], LCA [4], CFA [4], fewer codes blocked scheme [9], time code [14] and the combination of MSG-1 and code reservation assignment (CRA) [17] (represented by CRA + MSG1) schemes. For an MSG-1 and CRA combination, the tree capacity is divided such that the first-half of the tree handles calls by MSG-1 and the second-half handles calls with CRA design. The results in Figs. 5*a*–*c* show reduced code blocking in the proposed scheme for dominating non-real-time calls, uniform and dominating real-time calls. In Fig. 5*a*, it is shown that code blocking is less when the MSG-1 scheme is added with the CRA scheme. This is not true for a uniform distribution and low rates dominating scenario as the CRA scheme is good for a high rate dominating scenario. Even in case of high rates, superior performance comes at the expense of more cost and complexity. Multicode assignment blocking comparison of the maximum scattered group (MSG-n), where n indicates n OVSF codes facility for handling a new call is done with multicode scheme given in [2, 15]. The multicode assignment in [2] is represented by five dux-n, where d, u and x stand for decreasing strategy, united strategy and no reassignment used. Also, it uses CFA for code assignments. The multicode assignment in [15] called multicode multi rate compact assignment is represented by MMCA-n where n denotes the number of codes in the multicode. The results show the reduction in code blocking in the proposed single code assignment and reassignment schemes. The complexity of the proposed design is less because of using maximum scattered code groups in the first layer, it is possible to derive the maximum scattered vacant codes groups in all the remaining layers. The results in Figs. 5*d*–*f* show the reduction of blocking probability in the proposed multicode design compared with the existing schemes. For Fig. 5*d*, as in the case of single code design, the performance of multicode design can be slightly better if CRA is added but this will be at the expense of more cost and complexity factors.

5 Conclusion

OVSF codes are limited resources in 3 G and beyond WCDMA wireless networks. The occurrence of scattered vacant codes in the code tree because of random call arrivals and departure leads to more future high rate calls being blocked. The compact single code and multicode assignment schemes discussed in the paper use the most scattered vacant code(s) from the set of available codes reducing code/call blocking. The multicode design gives the additional benefit of handling non-quantised rates and reducing the code wastage capacity. Frequent call arrival and completion requires a regular update for the most scattered vacant group, which may increase the computation/decision time for new calls. The work can be extended to formulate decision time (because of online calculation of most scattered codes) and finding the optimum vacant code based on decision time and blocking probability. For real-time calls vacant code search can be made offline but it requires a large buffer size at the BS and UE.

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