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OVSF Code Sharing and Reducing the Code Wastage Capacity in WCDMA

Davinder S. Saini · Sunil V. Bhooshan

Abstract The non quantized nature of user rate wastes the code capacity in Orthogonal Variable Spreading Factor Codes (OVSF) based Code Division Multiple Access (CDMA) systems. The code sharing scheme in multi code CDMA is proposed to minimize the code rate wastage. The scheme combines the unused (wastage) capacity of already occupied codes to reduce the code blocking problem. Simulation results are presented to show the superiority of the proposed code assignment scheme as compared to existing schemes.

Keywords OVSF Codes · WCDMA · Rake combiners · Code assignment and reassignment

1 Introduction

In Wideband Code Division Multiple Access (WCDMA) [1], the uplink and downlink transmission is performed using two types of codes namely scrambling and channelization codes. While scrambling codes are used for device identification, channelization codes are used for channel separation. In WCDMA the channelization code are OVSF codes. OVSF codes are a limited resource because there is single OVSF code tree available for each Node B and User Equipment (UE). The channels used in the uplink are few. Hence there are enough OVSF codes for communication. For the downlink transmission, there are a large number of channels corresponding to transmission of signals from node B towards large number of UE. Therefore, for the downlink communication, the efficient use of the OVSF codes becomes important for better system performance. OVSF codes are generated from the binary tree generation given in [2]. The tree consists of large number of codes with the property that each code is not orthogonal to its ancestors and descendants. This leads to major drawback

D. S. Saini (✉) · S. V. Bhooshan
Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waknaghat, Distt. Solan, Himachal Pradesh, India
e-mail: davinder.saini@juit.ac.in

S. V. Bhooshan
e-mail: sunil.bhooshan@juit.ac.in

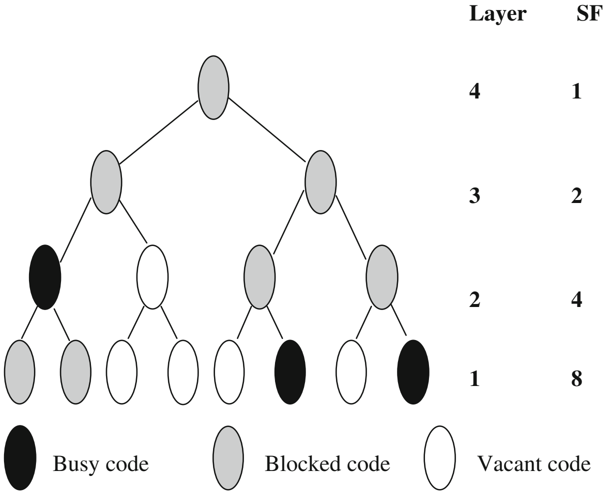

Fig. 1 Illustration of code blocking in 8R OVSF code tree

of OVSF codes called code blocking [3], according to which the system is unable to handle new call even when the system has enough capacity to handle it.

When a code is used in the code tree, all of its ancestors and descendants are blocked from assignment because they are not orthogonal. This is called code blocking which leads to call blocking. Basically the new call blocking is due to two limitations of OVSF-CDMA called external [4] and internal fragmentation [4]. The external fragmentation is because of the scattering of the vacant codes in the code tree whose internal fragmentation is due to quantized nature of the rate handling capability of the OVSF code tree. Figure 1 presents an OVSF code tree with maximum capacity 8R (R = 7.5 kbps) for the downlink of WCDMA. There are four layers with Spreading Factor (SF) 2^{4-l}, $l \in [1, 4]$. The code tree can handle rates $R, 2R, \ldots, 8R$. Out of $8R$ capacity, $4R$ is being used (due to ongoing calls of $2R$, R and R). If a new $4R$ user with requirement of layer 3 code arrives, it will be blocked despite of the fact that the sum of incoming rate $(4R)$ and used capacity $(4R)$ is not more than maximum capacity of code tree. So, we have a situation that the new call cannot be handled even though the code tree has enough capacity to handle it. This is called code blocking which leads to new call blocking. The remainder of the paper is organized as follows.

Section 2 describes the single code and multi code assignment and reassignment schemes proposed in literature. Section 3 explains the code capacity wastage problem and proposed code sharing using code time slots to minimize code wastage. Section 4 demonstrates the simulation results showing superiority of the proposed assignment scheme. The paper is concluded in Sect. 5.

2 Related Work

The code blocking due to internal and external fragmentation can be reduced by efficient assignment and reassignment of OVSF codes. The code assignment schemes can be broadly classified into single code and multi code assignment schemes. The single code assignment schemes intend to make code assignment compact such that the future rate arrivals encounter least blocking probability. Leftmost code assignment (LCA) [5], Random assignment (RA) [5], crowded first assignment (CFA) [5] are the few examples of single code assignment schemes. Leftmost code assignment does code assignment in the left of code tree such that the right side is free for future calls. The random assignment does code assignment randomly in the code tree. The crowded first assignment makes the current crowded portion of code tree more crowded aiming to produce least blocking for future high rate calls. The criterion for checking crowded portion may be the used capacity/space (CFS) or used codes (CFC) of the parents of the candidate vacant codes. Dynamic code assignment uses reassignments to minimize the code blocking. The extra overhead required for the reassignments increases the cost and complexity of the DCA [6] scheme. The dynamic code assignment with tree partitioning (DCA-TP) [7] works on the top of DCA providing better long term results using the tree partitioning and class aggregation. Code reassignments in [8] use proactive reassignments to reduce the overhead and complexity in DCA scheme.

The multi code assignment schemes are preferred for users with non quantized rates which can lead to external fragmentations. The use of multi code schemes requires multiple rake combiners at the Node B and UE. More channels are required to handle single call compared to single code assignment schemes. The call waiting time encountered in DCA is absent. The multi-code assignment scheme proposed in [4] reduces code blocking by significant amount. The code sharing described here works on the top of [4] with the additional ability of using wastage capacity of codes for future arrivals. The optimum selection of multi code is discussed in [9]. The multi code selection first lists one (all) possible candidate(s) with highest number of low SF codes. If unique result does not exists, the multi code with least number of codes is used for new call.

3 OVSF Code Rate Wastage and Code Sharing

3.1 OVSF Code Rate Wastage

Consider an OVSF-CDMA system with 8 layers as in the downlink of WCDMA system. Let us consider that the possible spreading factor in layer 1–8 (layer 1 corresponds to leaves and layer 8 corresponds to root) is $2^7, 2^6, \ldots, 2^0$. We intentionally use SFs $2^7, 2^6, \ldots, 2^0$ instead of $2^9, 2^8, \ldots, 2^2$ (in the case of WCDMA) for mathematical simplicity. The code in layer l, where $l \in \{1, 2, \ldots, 8\}$ is represented by $\mathrm{C}_{l,n}$ where n varies from $1, 2, \ldots, 2^{8-l}$. The maximum capacity of each layer and the system is 2^{8-l}. The number of codes and the spreading factor in layer l is 2^{8-l}. The data rate handled by the code in the layer l is $2^{8-l}R$. Consider a new user with data rate $k_1 R$ searching for vacant code(s) in the OVSF code tree. Define a multi-code $MC_i = [NC_8\text{: } NC_7\text{: } NC_6\text{: } NC_5\text{: } NC_4\text{: } NC_3\text{: } NC_2\text{: } NC_1]$, where NC_x is the number of codes in layer x used to handle rate $k_1 R$. The multi-code approach is used for incoming call in WCDMA system that utilizes multiple rake combiners. Define wastage capacity of a code (multi-code) as the ratio of code (multi-code) capacity utilized by the user to the maximum capacity of the code (multi-code). Assume there are N rake combiners in the WCDMA system. The wastage capacity (WC) of a multi-code is given by

$$WC = \left[\begin{array}{ll} 0 & k = \sum_{j=1}^{N} a_j 2^j,\ \text{where } a_x, x \in [1, N] \text{ takes values 0 or 1} \\ 0 & 0 < k < N - 1 \\ WC' & \text{where } WC' \text{ depends on the number of rakes } N \text{ and is given in Table 1.} \end{array}\right. \tag{1}$$

Table 1 OVSF code rate wastage variation with the number of rakes

Number of rakes	Wastage capacity (WC′)
1.	Assume $\mathrm{k} = \mathrm{k}_1$, $\mathrm{WC}' = 2^{\mathrm{a}_1} - \mathrm{k}_1$; $2^{\mathrm{a}_1-1} < \mathrm{k}_1 < 2^{\mathrm{a}_1}$
2.	Assume $\mathrm{k}_2 = \mathrm{k}_1 - 2^{\mathrm{a}_1-1}$ and $2^{\mathrm{a}_2-1} < \mathrm{k}_2 < 2^{\mathrm{a}_2}$, where $\mathrm{a}_1, \mathrm{k}_1$ is defined as for 1-rake system $\mathrm{WC}' = 2^{\mathrm{a}_2} - \mathrm{k}_2$; $2^{\mathrm{a}_2-1} < \mathrm{k}_2 < 2^{\mathrm{a}_2}$
3.	Assume $\mathrm{k}_2 = \mathrm{k}_1 - 2^{\mathrm{a}_1-1}$, $\mathrm{k}_3 = \mathrm{k}_2 - 2^{\mathrm{a}_2-1}$ and $2^{\mathrm{a}_3-1} < \mathrm{k}_2 < 2^{\mathrm{a}_3}$ where $\mathrm{a}_1, \mathrm{a}_2, \mathrm{k}_1$ and k_2 are defined as for 1, 2 rake systems $\mathrm{WC}' = 2^{\mathrm{a}_3} - \mathrm{k}_3$; $2^{\mathrm{a}_3-1} < \mathrm{k}_3 < 2^{\mathrm{a}_3}$
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8.	Assume $\mathrm{k}_\mathrm{g} = \mathrm{k}_{\mathrm{g}-1} - 2^{\mathrm{a}_\mathrm{h}-1}$, where $\mathrm{g} \in [2, 8]$ and $\mathrm{h} \in [1, 7]$, where $\mathrm{a}_1, \mathrm{a}_2, \ldots, \mathrm{a}_7$ and $\mathrm{k}_1, \mathrm{k}_2, \ldots, \mathrm{k}_7$ are defined as for rake $1, 2, \ldots, 7$ system $\mathrm{WC}' = 2^{\mathrm{a}_8} - \mathrm{k}_8$; $2^{\mathrm{a}_8-1} < \mathrm{k}_8 < 2^{\mathrm{a}_8}$

Table 2 Relation between data rate, maximum wastage capacity and number of rake combiners in WCDMA downlink

Input data rate	Maximum wastage capacity ($\mathrm{WC}_{\max}$) for 1 rake	$\mathrm{WC}_{\max}$ for 2-rake	$\mathrm{WC}_{\max}$ for 3-rake	$\mathrm{WC}_{\max}$ for 4-rake	$\mathrm{WC}_{\max}$ for 5-rake	$\mathrm{WC}_{\max}$ for 6-rake	$\mathrm{WC}_{\max}$ for 7-rake
<2R	0	0	0	0	0	0	0
<4R	1	0	0	0	0	0	0
<8R	3	1	0	0	0	0	0
<16R	7	3	1	0	0	0	0
<32R	15	7	3	1	0	0	0
<64R	31	15	7	3	1	0	0
<128R	63	31	15	7	3	1	0

Using the formulae in Table 1, for an OVSF-CDMA system with N rake combiners and user rate less than $2^x R$, where $x \in [0, 7]$, the maximum code wastage capacity is $(2^{x-N} - 1)R$ and is shown in Table 2 for WCDMA system with 8 layer OVSF code tree.

3.2 Code Sharing and Reduction in Wastage Capacity

For N rake system, consider a new call with rate $k_1 R$, where $2^{a_1-1} < k_1 < 2^{a_1}$, the procedure starts dividing the rate into quantized and non quantized parts. Assign vacant code with capacity $2^{a_1-1}R$ to the portion of the call.

For $k_2 = k_1 - 2^{a_1-1}$, if k_2 is quantized, the vacant code with code capacity $k_2 R$ is assigned to the $k_2 R$ portion of $k_1 R$. If $k_2 R$ is not quantized, then for $2^{a_2-1} < k_2 < 2^{a_2}$, find $k_3 = k_2 - 2^{a_2-1}$ and repeat the procedure for maximum $N - 1$ times. The procedure is repeated $N - 1$ times if the rate k_x, $x \in [1 : N - 1]$ is non zero. For this case, code wastage takes place and the code wastage amount is $k_N - 2^{a_N-1}$, where $2^{a_N-1} < k_N < 2^{a_N}$. The portion $k_N R$ of the rate $k_1 R$ is assigned to the vacant code and unused code capacity of the code is $WC_1 = (2^{a_N} - k_N)R$. For the next non quantized incoming calls find WC_2, $WC_3, \ldots, WC_M$ similar to WC_1, if any. If the new call with the rate requirement of $k'R$ where, $\mathrm{k}'R = \sum_{i=1}^{t} m_i k_i R + \sum_{j=1}^{N-t} WC_j$, where $m_i \in [0, 1]$ and $1 \le t \le N$ arrives, the code portions $WC_1, WC_2, \ldots, WC_{N-t}$ can be combined to handle new call. Therefore the code sharing allows the integration of vacant slots (code portions) to fulfill the request of

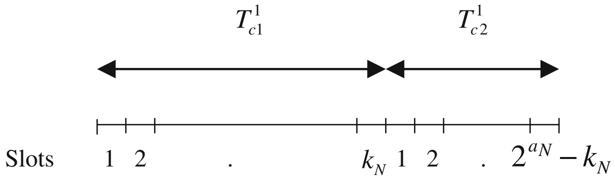

Fig. 2 Division of time slots to handle non-quantized calls

new user. For quantized data rates, the capacity is zero. The slot management is the important part of the proposed code assignment scheme. In the following paragraph, the code sharing is explained for single rake system.

To illustrate code sharing, for a new call $k_1 R$ equipped with N rake combiners, the wastage capacity *WC* (if any) is $WC = 2^{a_N} - k_N$, where a_N and k_N are defined earlier. Consider T_c as the time frame of code in layer 8. The code time in layer 8 is divided into 128 time slots with slot time $T_{slot} = T_c/128$. The duration of the time frame for a code in layer l is 2^{l-1} slots. The number of slots in layer $l, l \in [1, 8]$ are given by 2^{l-1}. Define T_c^x as the fraction of the code time frame used by xth call. If a call with rate $k_1 R$ leads to wastage capacity *WC*, the time of the code captured by the new call is divided into two components given by

$$T_c^1 = T_c^1 \left(\frac{k_N}{2^{aN}}\right) + T_c^1 \left(\frac{WC}{2^{aN}}\right) = T_{c1}^1 + T_{c2}^1 \tag{2}$$

The division of time slots is shown in Fig. 2. The code portion T_{c1}^1 (k_N number of slots) is used to handle portion of $k_1 R$ call. The portion $T_{c2}^1(2^{a_N} - k_N$ number of slots) can be used for the future call. For Lth new call, the vacant code frame slots can be combined if

$$T_c^L = \sum_{i=1}^{L-1} T_{c2}^i \tag{3}$$

Code slot management is the important part of the proposed design and the maximum number of code time frames accumulated is equal to number of rake combiners.

To illustrate code assignment scheme, consider the arrival of four calls $7R$,$6R$,$11R$ and $2R$ for $32R$ capacity system equipped with 2 rake combiners as shown in Fig. 3. The codes used to handle $7R$, $6R$ and $11R$ calls are [$C_{4,1}$], [$C_{3,3}$ and $C_{2,7}$] and [$C_{4,3}$ and $C_{3,7}$] respectively as shown in Table 2. The wastage capacity for codes used are $1R$,$0R$ and $1R$ respectively. The new call with $2R$ rate, uses the wastage capacities WC_1 and WC_3 for data transmission. This is equivalent to add time slot T_{ref} available with code $C_{4,1}$ and time slot T_{ref} available with code $C_{3,7}$ to fulfill the time requirement of $2R$ call (Table 3).

4 Simulation Results

4.1 Input Parameters

- Call arrival process is assumed to be Poisson distributed with average value, $\lambda = 1$–128 calls/time.
- Service time is assumed to be negative exponential distributed with mean value $1/\mu = 1$ units of time.

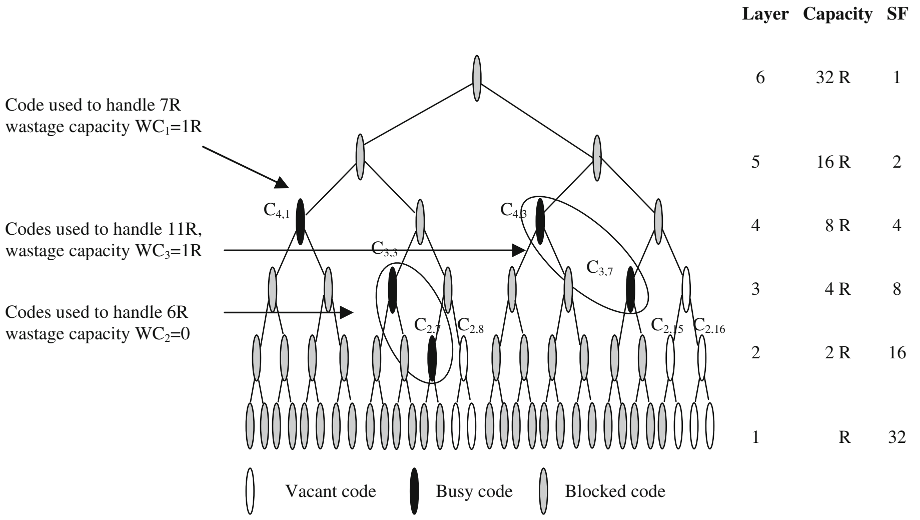

Fig. 3 Illustration of multi code assignment scheme with provision of slot integration

Table 3 Code assignment and wastage capacity for 7R, 6R and 11R calls

Call arrivals	Codes used	Wastage capacity
7R	$C_{4,1}$	1R
6R	$C_{3,3}$ and $C_{2,7}$	0
11R	$C_{4,3}$ and $C_{3,7}$	1R

- Two categories of rates are assumed quantized and non quantized. In quantized rates, there are eight classes of users with rates $R, 2R, 4R, \ldots, 128R$ ($R = 7.5\,\text{kbps}$). For non quantized rates, there are 128 classes of users with rates $R, 2R, 3R, \ldots, 128R$.
- The capacity of OVSF code tree is $128R$ with root in layer 8 (layer numbering starts from leaves).

4.2 Quantized Data Rates

Consider that there are G_k, $k = 1, 2, \ldots, 8$ servers in the k_{th} layer corresponding to G_k number of vacant codes. The total codes (servers) in the system assuming eight set of classes are the given by set $G = \{G_1, G_2, G_3, G_4, G_5, G_6, G_7, G_8\}$. The maximum number of servers used to handle new call is equal to the number of rake combiners. Letλ_k,μ_k is the arrival rate, service rate of kth class of users. Traffic load for the kth class of users is given by $\rho_k = \lambda/\mu$. The code blocking for the kth class is defined by

$$P_{B_k} = \frac{\rho_k^{G_k}/G_k!}{\sum\limits_{n=1}^{G_k} \rho_k^n/n!} \tag{4}$$

The average code blocking for 8 class system is

$$P_B = \sum_{k=1}^{8} \frac{\lambda_k}{\lambda} P_{B_k} \tag{5}$$

We divide the eight classes of calls into two categories namely real time classes (with rates R, $2R$, $4R$ and $8R$) and non real time calls (with rates $16R$, $32R$, $64R$ and $128R$). Let the arrival distribution for the four classes is given by $[p_1, p_2]$, where p_1 and p_2 is the probability of real time and non real time calls. Three arrival distributions are considered as given below

- [0.75,0.25] for low rate calls dominating the arrival process;
- [0.5,0.5] for uniform distribution of eight classes;
- [0.25,0.75] for high rate calls dominating the arrival process.

The blocking probability of the proposed design named multi code assignment with code sharing in N rake system (MC-CS-N) is compared with the blocking probabilities of LCA, CFA, multi-code with N rake system (MC-N) assignment schemes discussed in Sect. 2. The results are obtained using event driven simulations in MATLAB 7 with built in tree functions The DCA and DCA-TP gives zero blocking with overhead of reassignments. The reduction in call blocking is shown in Figs. 4a–c.

4.3 Non Quantized Data Rates

Consider there are 128 classes of users with rates $R, 2R, \ldots, 128R$. The arrival rate and service rate is λ_k and $\mu_k, k \in [1, 128]$. The non quantized rates are first converted into quantized rates as discussed in Sect. 3.2. For each of the quantized data rates, the code blocking can be calculated using Eqs. 4, 5. The average code blocking is given by

$$P_B = \sum_{k=1}^{128} \frac{\lambda_k}{\lambda} P_{B_k} \tag{6}$$

The arrival distribution for the 128 classes is divided into two sets defined by $[p_1, p_2,]$, where p_1 is the sum of probabilities of rate arrival λ_i, $i \in [1, 15]$ assumed to be real time calls and p_2 is the sum of probabilities of rate arrival λ_i, $i \in [16, 128]$ assumed to be non real time calls. Three distributions of rates are assumed

- [0.75, 0.25] for low rate calls dominating the arrival process;
- [0.5, 0.5] for uniform distribution of four classes;
- [0.25, 0.75] for high rate calls dominating the arrival process.

The blocking probability of the proposed design MC-CS-N is compared with the blocking probabilities of LCA, CFA, MC-N, DCA and DCA-TP schemes. The blocking probability with non quantized rates is more than quantized rates due to external fragmentation. Simulation is performed for 10,000 calls and result is the average over 10 simulations. The reduction in call blocking is shown in Figs. 4d–f. The code blocking reduces as the number of rake combiners is increased.

5 Conclusions

Multi code assignment schemes are superior to single code assignment schemes in handling non quantized data rates. Multi code scheme discussed in the paper uses the code wastage capacity of the existing busy codes for handling new calls. Code sharing and time frame division gives better performance especially for systems equipped with few rake combiners. The number of rake combiners required is less compared to existing multi code schemes for similar performance. The complexity of the proposed scheme increases with the increase in

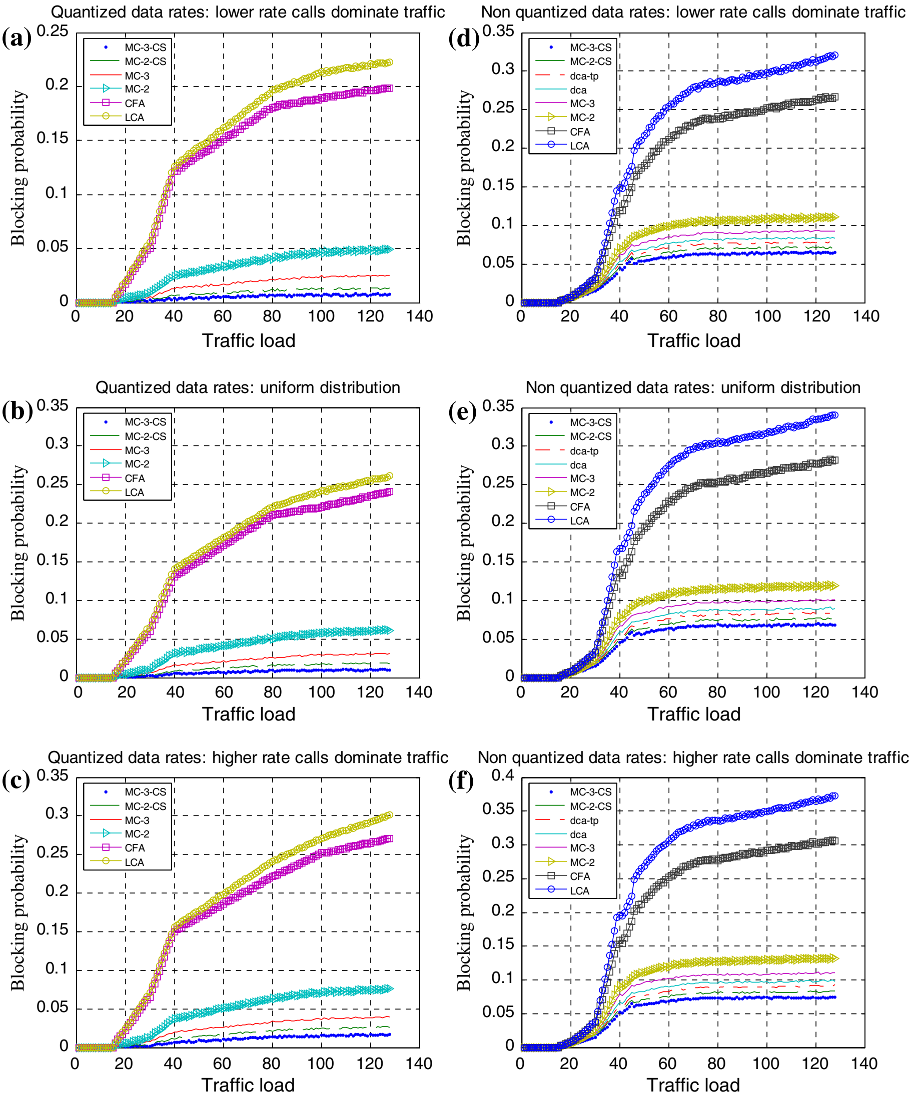

Fig. 4 Comparison of the blocking probability in the proposed scheme with existing schemes considering following scenarios. (**a**) Quantized input rates with lower rate calls dominating, (**b**) quantized input rates with uniform distribution, (**c**) quantized input rates with higher rate calls dominating, (**d**) non-quantized input rates with lower rate calls dominating, (**e**) non-quantized input rates with uniform distribution and (**f**) non-quantized input rates with higher rate calls dominating

the number of codes shared and number of rakes used at Node B and UE. So, the compromise is between the number of rake combiners and time slots management complexity. The time slot management can be worked out to produce least complexity.

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Author Biographies

Davinder S. Saini received his B.E. degree from Marathwada University, Aurangabad, India in 1998. He received M.Tech Degree from the Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee, Roorkee, India in 2001. He completed his PhD. in Channelization codes in third generation and beyond systems in the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waknaghat, India. He is currently Assistant Professor in the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, India. His research include third generation and beyond Mobile communication Systems, Wideband CDMA channelization codes, Ad hoc networks.

Sunil V. Bhooshan completed his basic engineering B.Tech. degree from Indian Institute of Technology, New Delhi from the Department of Electrical Engineering. After completing B.Tech. he joined the post graduate program of the University of Illinois at Urbana-Champaign where he completed his M.S. and Ph.D. degrees from the Department of Electrical Engineering. Here he worked on his thesis project/research, and also on projects from industry on a consultancy basis assisting his thesis advisor. He joined Hewlett-Packard at their Network and Measurement Division at Santa Rosa California where he worked on a number of measurement related projects which were to materialize as a product/parts of a product which were to be later marketed by the company. Briefly he joined the Electrical Engineering Department of the Indian Institute of Technology, Kanpur as Assistant Professor. He is currently Head of the Department in Department of Electronics and Communication Engineering, Jaypee University of Information Technology, India.