OVSF CODE ASSIGNMENT SCHEMES AT THE FORWARD LINK OF WCDMA

by

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CERTIFICATE

It is certified that the thesis entitled *OVSF Code Assignment Schemes at the forward link of WCDMA* is being submitted by *Davinder Singh Saini* for the award of degree of Philosophy in Electronics and Communication to the *Jaypee University of Information Technology, Waknaghat*, is a bonafide record of research work done under my guidance and supervision.

The thesis has reached the standard fulfilling the requirements of the regulations relating to the degree. The results obtained in the thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

(Sunil V Bhooshan)

Dedicated to my Parents

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CONTENTS

ABSTRACT

The Wideband Code Division Multiple Access (WCDMA) reverse link and forward link transmission is done using two codes namely scrambling code and channelization code. The scrambling code is used for device identification and channelization code is used for channel separation. The channelization codes in WCDMA are Orthogonal Variable Spreading (OVSF) codes. OVSF codes are limited resources because there is single OVSF code tree available at each base station and User Equipment (UE). In the reverse link, single UE transmits to single Base Station (BS), requiring fewer codes. Hence there are enough OVSF codes for communication. For the forward link transmission, single BS transmits signal to large number of UEs within cell, requiring large number of codes. So for the forward link communication, the efficient use of the OVSF codes becomes important for better system performance. The OVSF code tree consist of large number of codes with the property that a code is not orthogonal to its ancestors and descendants. This leads to major drawback of OVSF codes called code blocking according to which, the system is unable to handle new call even the system has enough capacity to handle it. The code blocking further gives rise to two limitations of OVSF-CDMA system called as internal fragmentation and external fragmentation. The internal fragmentation is due to the quantized nature of rate handling capability of OVSF codes. The external code fragmentation is to the vacant scattered codes which make the code tree too fragmented to handle new incoming calls. The thesis aims to improve the performance of WCDMA system in terms of reduction in OVSF code blocking probability, handling non-quantized rates, reducing the codes searched and QoS provision etc. The rest of the thesis is organized as follows.

Chapter 1 presents the use of channelization codes and scrambling codes as the spreading codes in WCDMA along with the essential properties of each code.

In chapter 2 the review of OVSF-CDMA is given. The code blocking problem is discussed along with internal and external quantization. The novel schemes published in the literature are being discussed with the merits and demerits.

Chapter 3 to 6 discusses the different contributions of the author in OVSF code assignment and reassignment schemes. In chapter 3 Fast code assignment and reassignment schemes are proposed. The reserve brother assignment (RBA) scheme does code assignment adaptive to the traffic load distribution. The adaptive tree properties

(ATP) scheme does the code reservation for the new calls depending upon the tree properties like number of busy trees, the available capacity and number of vacant codes etc. Fast Assignment (FA) scheme divides the codes in upper layers into two sets known as assign tree set and block tree set. The codes in the assign tree set are used explicitly for assignment and codes in the block tree set are used only for blocking. The descendants of the codes are shifted to reduce the number of code searches. The fast reassignment (FRA) scheme divides the codes into three sets named assign tree set, block tree set and spare tree set where the additional spare tree set uses traditional way of code assignment and blocking.

Chapter 4 discusses different way to utilize the codes in the multi-code OVSF system. The multi-code assignment scheme uses more than one code to handle non-quantized data rates. The use of more codes requires more rake combiners increasing the complexity in the receiver. Higher is the number of codes used in the multi-code, higher is the complexity of system. The code assignment procedure is divided into three steps. The first step is to list all possible combinations of codes available to handle incoming call. The second step lists the combinations with unique arrangement and multiple arrangements. The final step is to pick the best possible combination to use minimum codes and least fragmentation. The methods to minimize code fragmentation and code wastage are also discussed.

Chapter 5 discusses compact single code assignment schemes. The priority based code assignment scheme divides the total codes in the code tree into two classes namely as real time class and best effort class. According to the type of incoming call the availability of code is checked in the appropriate layer. For the best effort traffic, the threshold is decided for each layer which tells the capability of the layer to handle real time call. For the real time type calls, the availability of the vacant code is checked in the corresponding layer of the real time call. If the vacant code is not available the threshold for the number of busy codes is checked in the best effort type layers. If the threshold is not exceeded in any of the best effort layer, the code rate is divided into two parts. The first part is equal to the code with the rate of the incoming call and second part is the remaining capacity of the code. The compact code assignment (CCA) scheme, assigns the code to the new incoming call in such a way that the remaining capacity of the system is least fragmented making the assignment scheme most compact. This leads to improved performance of the OVSF-CDMA system. Results show that the CCA scheme can outperform the schemes that do not consider the code assignment on the basis of code groups. The next code precedence high (NCPH) code assignment scheme provides an efficient way to use OVSF codes. The code tree is less fragmented due to the compact nature of code assignment scheme.

Chapter 6 discusses few additional code assignment schemes independent of the code tree properties to reduce code blocking. In code tree extension, the traditional 8-layer OVSF code tree is extended into 10-layer code tree. The three additional codes in the layer 8 increase the code capacity to four times the capacity of traditional 8 layer code tree. The bandwidth division assignment (BDA) code assignment scheme has the advantage that the code blocking can be made as small as zero because of ability of rate division at the input in small quantized rates. The internal fragmentation can also be made zero because of the rate division. We also proposed a design giving zero code blocking. It considers the use of OVSF code tree in the UE for the forward link communication. The code/call blocking can be completely eliminated. The single code time multiplexing (SCTM) uses single code sharing by multiple users to reduce code blocking.

The thesis is concluded in chapter 7 and the directions to the future work are given.

CHAPTER 1

Introduction

The third generation (3G) systems are superior to second generation (2G) systems in terms of supporting multimedia rates, variable bit rates, facility for QoS provision etc. The current 2G systems in use are GSM in Europe, IS54/IS136 in USA, PDC in Japan and IS95 USA CDMA standard etc. The 3G (also known as international mobile telecommunication IMT2000) standards are given in the Figure 1.1. The outer ring in

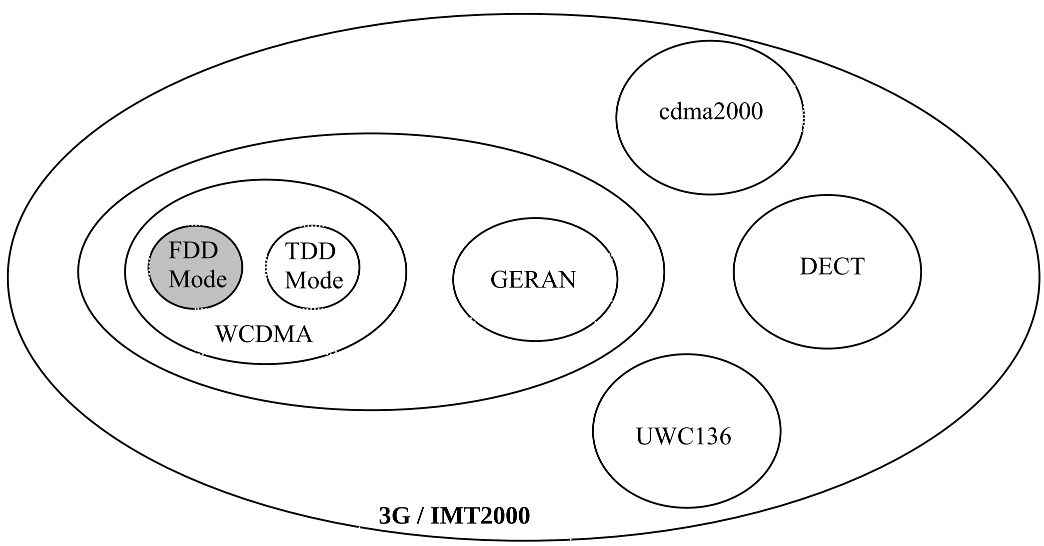


Figure 1.1 3G technology relationship

Figure 1.1 illustrates the extent of 3G technologies and different terms applied to define 3G. The smaller rings within the outer ring constitute 3G. The thesis discussion is only limited to the shaded part of 3G spectrum (WCDMA in FDD mode). The other standards like GSM/EDGE Radio Access Network (GERAN), Digital Enhancement Cordless Telephone (DECT), Universal Wireless Communication (UWC) and cdma2000 will not be discussed. WCDMA/UTRA-FDD [1,2,3] is the leading 3G standard and under immense research under 3GPP[4,5]. It differs from most of the 2G systems due to use of direct sequence multiple access method [6,7,8]. The architecture of the UTRA-FDD system is given in [9,10]. Some of the parameters of WCDMA system are given in Table 1.1.

Two important issues under research in WCDMA systems are spreading codes [11,12,13] and modulation[14]. Spreading is the fundamental operation of WCDMA radio interface. The spreading codes in WCDMA are of two types namely channelization

Table 1.1 Main WCDMA parameters

Multiple access method	DS-CDMA
Carrier spacing	5MHz
Chip rate	3.84 Mcps
Frame length	10ms
Duplexing method	Frequency division duplex
Detection	Coherent using pilot symbols and common pilot
Base station synchronization	Asynchronous operation
Modulation	Coherent QPSK in the forward link and Coherent BPSK in the reverse link
Channelization code	OVSF code with SF 4 to 512 in the forward link and 4 to 256 in the reverse link
Scrambling code	Gold codes, Kasami codes

code and scrambling code. The channelization codes in WCDMA are OVSF codes. The channels in the forward link and reverse link use theses codes for transmission. OVSF codes are shorter in length and are made from orthogonal function. The orthogonality property of OVSF codes makes it suitable for WCDMA. The signals from two or more UEs in the reverse link are transmitted to same BS in the cell from separate locations. This change in distance gives rise to change in time for the signals to reach at the BS. The orthogonal property of the OVSF codes is disturbed due to different arrival times. Hence the OVSF codes are not used for user separation in the reverse link. The facility to handle variable user rate is also incorporated in OVSF codes. In contrast to OVSF codes, scrambling codes are quite long (with the exception of the reverse link of the short scrambling code). Scrambling codes are generated from the stream called

Table 1.2 Spreading codes for IS95 and WCDMA

Link	**Channelization code**	**Scrambling code**
IS95 forward link	Walsh code	Time shifted M sequence
IS95 reverse link	N/A	Time shifted M sequence
WCDMA forward link	OVSF code	Gold code
WCDMA reverse link	OVSF code	Kasami code

pseudo noise (PN) sequences [15]. The use of spreading codes in IS95 CDMA and WCDMA is shown in Table 1.2. In WCDMA the requirement is have codes with high value of autocorrelation and low value of crosscorrelation. High autocorrelation properties are desired to recover the intended signal and to reduce the effect of multipath signals. The low crosscorrelation properties are required to minimize the effect of interfering signals. The PN codes and orthogonal codes individually do not have both good autocorrelation and good crosscorelation properties.

1.1 Psuedonoise Sequences

PN sequences are used in the WCDMA due to excellent autocorrelation properties. PN sequences are deterministic sequences that exhibit randomness properties similar to

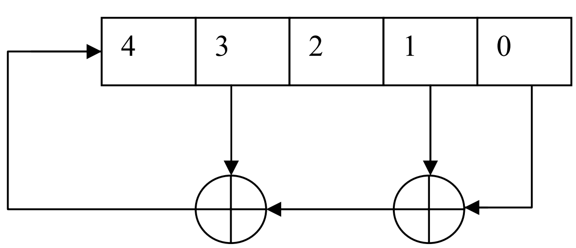


Figure 1.2 Linear feedback shift register

sampled white Gaussian noise. Since PN sequences are deterministic, they can be generated or stored at the receiver to despread incoming signals. PN sequences are typically generated using a Linear Feedback Shift Register (LFSR), as illustrated in Figure 1.2. The sequence generated by a LFSR is periodic with a maximum period of N $= 2^n-1$, where n is the number of stages in the shift register. A LFSR sequence with the maximum possible period is called a Maximal-Length Sequence (M-sequence). A generator polynomial is typically used to describe a LFSR, with each non-zero term

Table 1.3 Maximal-length sequences

Shift registers	Code length	Number of codes
3	7	2
4	15	2
5	31	6
6	63	6
7	127	18
8	255	16
9	511	48

corresponding to a feedback connection. The generator polynomials that produce M-sequences for LFSRs with up to thirty-four shift registers are tabulated in [16]. Table 1.3 gives the M-sequence code length and the number of unique M-sequences for shift registers of various lengths. Properties of M-sequences which make them appear random [17] are listed below.

1. *Balance Property*. In each period of the sequence, the number of binary ones differs from the number of binary zeros by at most one.
2. *Run Property*. In each period of the sequence, about one-half of the runs are of length one, one-fourth of the runs are of length two, one-eighth are of length three, and so on. A run is defined as a sequence of all binary ones or all binary zeros and the length is defined as the number of digits in the run.
3. *Autocorrelation Property*. If a period of the sequence is compared term by term with any cyclic shift of itself, the number of digits that agree and the number of digits that disagree will differ by at most one.

The autocorrelation properties of PN sequences are very good for both detection of the desired signal, and rejection of multipath signals. The PN autocorrelation function

(Figure 1.3) has a maximum value of one when the codes are perfectly synchronized, and has a value of -1/N when the time delay (τ) is greater than the chip time (T_c). This

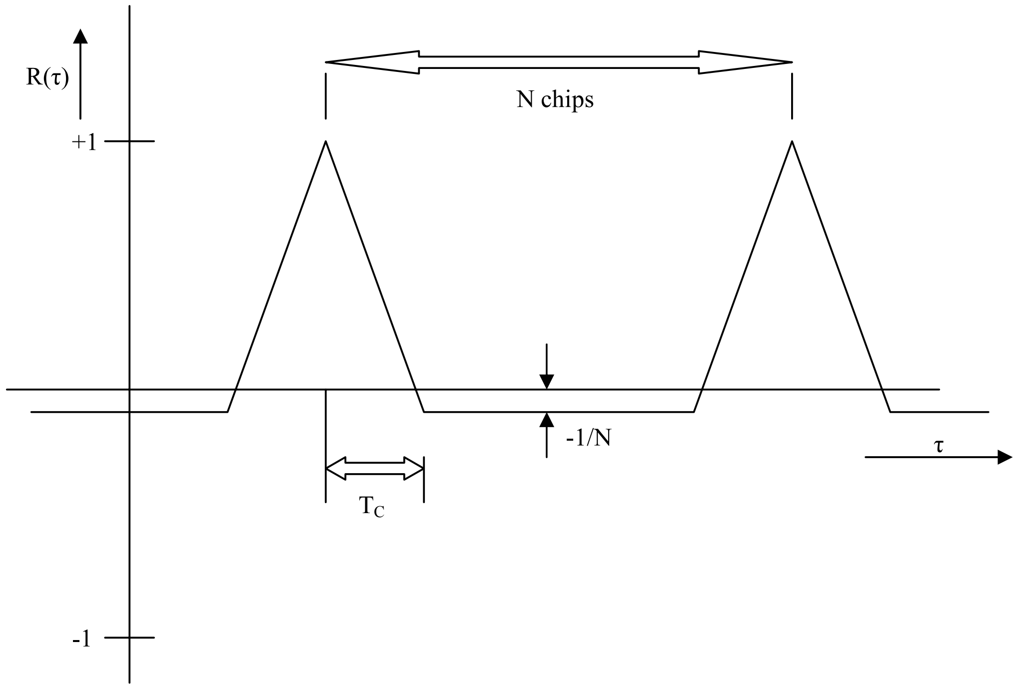


Figure 1.3 PN autocorrelation function

property of the PN autocorrelation function is useful in overcoming the relatively weak cross-correlation properties of PN sequences. For PN sequences with long periods, the autocorrelation between the original code and a time shifted version of the same code is approximately zero. Therefore, time shifted versions of a single PN sequence can be effectively utilized as different DS spreading codes. The drawback of this approach is that it requires synchronization between users in the system. The IS-95 CDMA cellular network is an example of a synchronous system that uses time shifted PN sequences as different spreading codes. An alternative approach is to linearly combine carefully selected M-sequences, which results in a sequence with both good autocorrelation properties and bounded cross-correlation properties. Gold Codes and Kasami Codes are both generated by combining the M-sequences from different LFSRs.

1.2 Orthogonal Codes

Orthogonal codes are sets of binary sequences that have a cross-correlation coefficient equal to zero. A set of periodic signals is orthogonal if Equation 1.1 is satisfied for all signals in the set. In Equation 1.1, T is the period of the signals $s_i(t)$ and $s_j(t)$, and E is the signal energy as defined in Equation 1.2. The set of signals representing the orthogonal

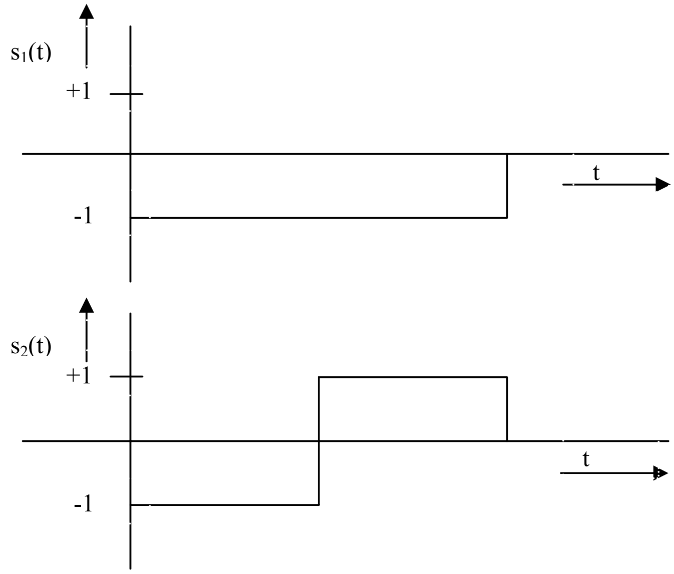


Figure 1.4 Orthogonal signals

binary sequences 00 and 01 is shown in Figure 1.4.

$$\frac{1}{E}\int_0^T s_i(t)s_j(t)dt = \begin{cases} 0 & \text{i} \neq \text{j} \\ 1 & \text{i} = \text{j} \end{cases} \qquad (1.1)$$

where

$$E = \int_0^T s_i^2(t)dt \qquad (1.2)$$

Table 1.4 Spreading code usages in the forward link and reverse link

Code Type	**Code use in reverse link**	**Code use in forward link**
Channelization code	Data rate control	User separation Data rate control
Scrambling code	User separation Interference mitigation	Interference mitigation

The use of channelization codes and scrambling codes are different in the reverse link and forward link and is given in Table 1.4. Figure 1.5 illustrates the use of spreading codes. For the reverse link transmission, the scrambling codes and channelization codes are different. For the forward link transmission same scrambling code is used for

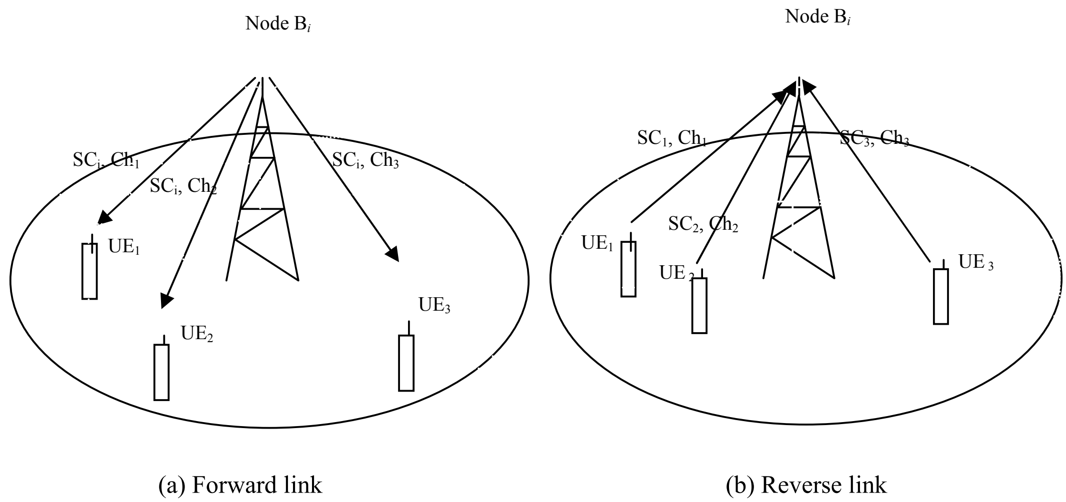


Figure 1.5 Scrambling and channelization code usage in WCDMA. Figure 1.5(a) shows the forward link transmission from i^{th} node (Node B_i) to three UEs. All the channels use same scrambling code and different channelization code. Figure 1.5(b) shows reverse link transmission from three UEs to Node B_i. All channels/users use different scrambling codes.

channels corresponding to each UE. Hence in the forward link transmission the efficient use of channelization code becomes important. The OVSF codes are generated from the code tree generation given in [18,19,20]. One of the properties of OVSF codes is that when a code is assigned to new call, all of its ancestors and descendants are blocked from the assignment. This is due to the fact that, the codes from root to leaf are not orthogonal to each other. This leads to code blocking which further produces the new call blocking. Basically the new call blocking is due to two limitations of OVSF-CDMA called as internal fragmentation and external fragmentation [21]. The external fragmentation is because of the scattering of the vacant codes in the code tree. The internal fragmentation is due to quantized nature of the rate handling capability of the OVSF code tree. Previous to OVSF codes, OCSF (Orthogonal constant spreading factor) codes were being used. All OCSF codes have same number of chips (spreading factor). For higher rate user more OCSF codes are used. Major limitation of OCSF-CDMA (MC-CDMA) system is that the numbers of transceiver units required are same as the number of OCSF codes used. So, higher rate user needs more transceiver units. This increases hardware complexity for higher rate users. A number of code assignment and reassignment schemes are proposed in literature to avoid code blocking. The thesis aims to reduce/eliminate OVSF code blocking.

WCDMA specify four different traffic classes namely conversational, streaming, interactive and background with different QoS requirements. The typical QoS parameters are throughput, delay, power and capacity etc. The traffic corresponding to each class needs to be treated differently. Real time calls are always given higher priority compared to the non real time classes. The requirement of different QoS is discussed in [26,27,28].

Table 1.5 Relationship between data rates and spreading factor (SF) in the forward link of WCDMA system

Data Rate (kbps)	Spreading Factor	Channel Chip Rate (Mcps)
7.5	512	3.84
15	256	3.84
30	128	3.84
60	64	3.84
120	32	3.84
240	16	3.84
480	8	3.84
960	4	3.84

The possible data rates for the WCDMA are R, 2R, …., 128R (where R is 7.5kbps for forward link and 15kbps for reverse link). The spreading factor of OVSF codes varies as 4,8,….,512 in the forward link and 4,8,….,256 in the reverse link. As discussed earlier, the channel chip rate in WCDMA is fixed equal to 3.84 Mcps. To make data rate compatible with the channel chip rate, the SF of the code chosen in OVSF code tree should be such that the product of data rate and SF is equal to 3.84 Mcps. Table 1.5 gives the possible data rates and spreading factors in the forward link providing the fixed chip rate (3.84 Mcps) in the WCDMA systems.

1.3 Research Problem

As discussed in previous sections, code blocking is severe problem in OVSF codes. The efficient OVSF code assignment becomes important to improve the performance of WCDMA systems. The choice of code assignment scheme depends on the following criterion

- Number of rake combiners required e.g.[29,30]
- Ability to handle non-quantized data rates [29]
- Number of reassignments required [31
- Code utilization e.g.[32]
- Blocking probability e.g.[33,34]
- Throughput e.g.[35,36]
- Fairness and scheduling e.g.[37,38,39,40] etc.

A number of code assignment schemes are already proposed in literature. The thesis aims to add more options for the efficient assignment of OVSF codes.

CHAPTER 2

Review of OVSF-CDMA

2.1 UMTS/IMT2000 architecture

The WCDMA air interface is part of the overall IMT-2000 system architecture, which is logically divided into the core network, UMTS Terrestrial Radio Access Network (UTRAN), and User Equipment (UE). The labels U_u and I_u refer to the protocol interfaces between the UE and UTRAN, and UTRAN and core network respectively. This is illustrated in Figure 2.1. The core network contains the Mobile Switching Center (MSC), GGSN, and SGSN, which currently exist as part of the GSM and GPRS core

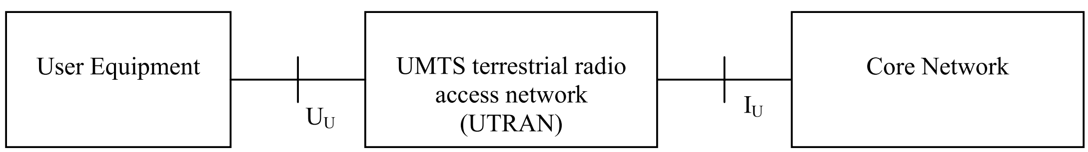


Figure 2.1 IMT2000 system architecture

network. In addition to switching and control functions, the core network provides access to the Public Switched Telephone Network (PSTN), and public data networks. UTRAN consists of the Radio Network Controller (RNC) and Node Base stations (Node B). These components provide wireless access for the UE. The connectivity between components in the IMT-2000 reference architecture is shown in Figure 2.2.

The protocol architecture for IMT-2000 is logically divided into the access stratum and the non-access stratum. The interface protocols in the access stratum terminate in the UTRAN, while those in the non-access stratum terminate in the core network. Information is exchanged between the access and non-access strata at both the UE, and the core network. This logical separation is illustrated in Figure 2.3. The protocols are also separated into the control plane and the user plane. Control plane protocols provide signalling functions such as call admission, call setup, resource

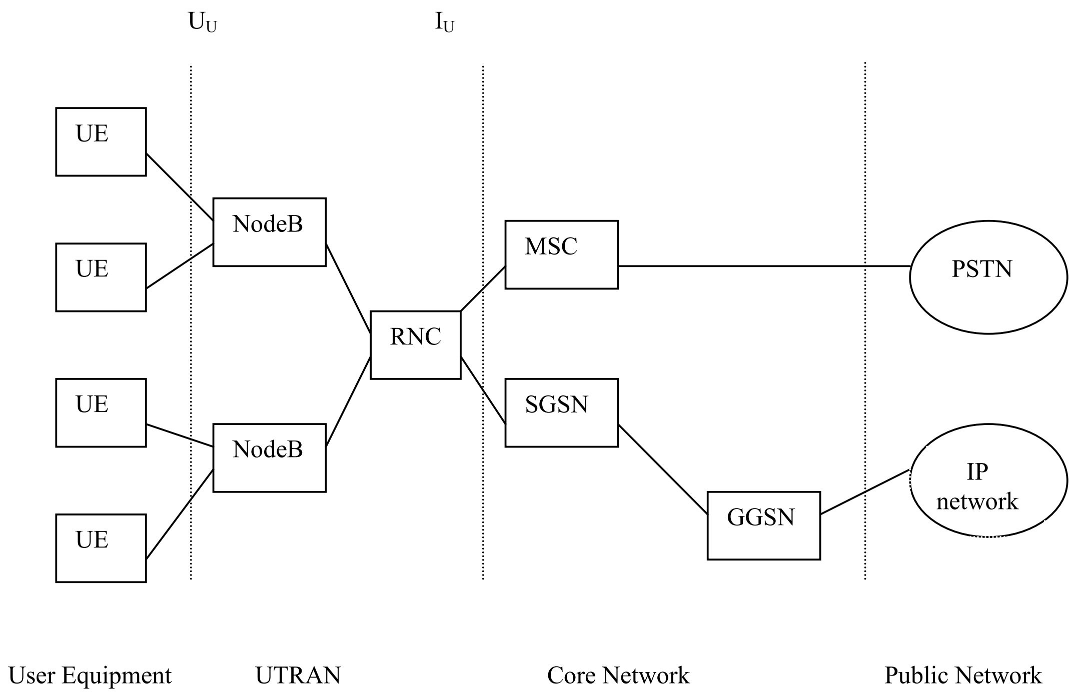


Figure 2.2 IMT2000 reference architecture

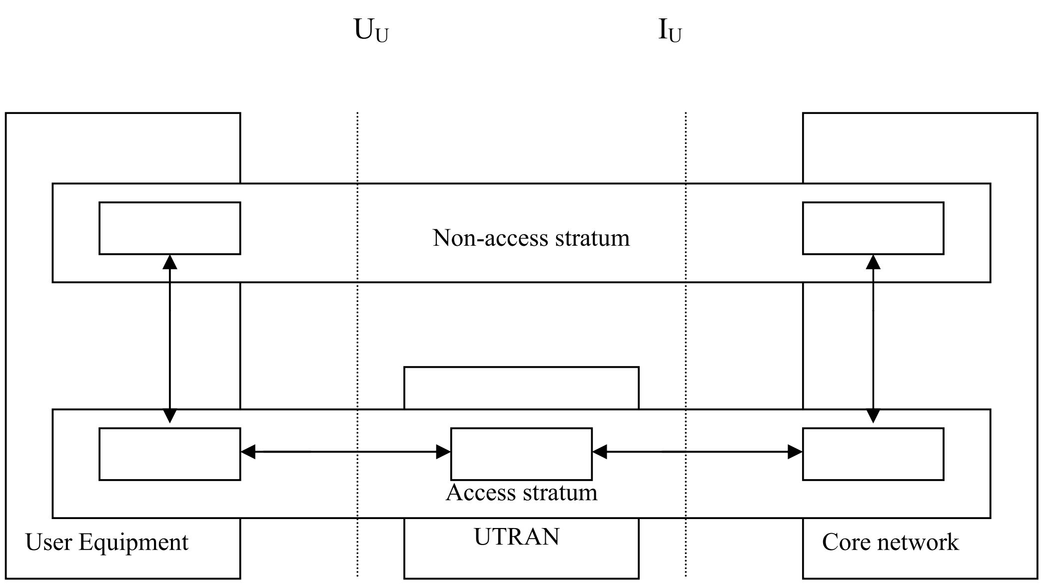


Figure 2.3 Access and non-access protocol

management, and mobility management. User plane protocols provide the actual transfer of user data. Layer one consists of the physical layer (PHY) in both the user and control planes. Layer two contains the Medium Access Control (MAC) and Radio Link Control (RLC) sublayers in both the control and user planes. In addition, layer two of the user plane may contain the Packet Convergence Data Protocol (PCDP), and the Broadcast

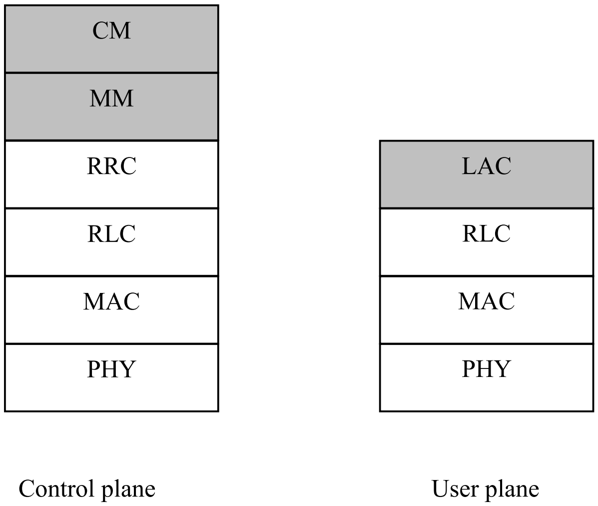


Figure 2.4 WCDMA protocol stacks

Multicast Control (BMC) sublayers. Layer three consists of the Radio Resource Control (RRC), Mobility Management (MM), and Call Management (CM) sublayers in the control plane. In the user plane, layer three is the Link Access Control (LAC) protocol. The control plane and user plane protocol stacks are shown in Figure 2.4, where shaded layers indicate non-access stratum protocols that terminate in the core network.

2.1.1 Physical Layer

The WCDMA physical layer uses DSSS with a chip rate of 3.84 Mcps. WCDMA uses a 10ms frame, which is broken up into 16 slots of 0.625 ms. This short frame structure allows low delay voice traffic and fast control messages [41]. OVSF codes, called channelization codes, are used to spread the data in each frame. In the uplink, the data rate supported by each frame is 15×2^k kbps, corresponding to a SF of $256/2^k$, where $k = 0, 1, \cdots, 6$. The SF of the OVSF code can be changed for each 10 ms frame. The maximum data rate supported in a frame is 960 kbps. On the downlink, control and data slots are time multiplexed. QPSK modulation is used to increase the downlink data rate to 1.92 Mbps, using the same channelization code to spread both I and Q channels. The tree of OVSF codes can be reused in each cell. A cell unique PN sequence, called a scrambling code, is applied after the channelization code to separate users in adjacent cells. On the uplink, user data and control data are transmitted separately on the I and Q channels. Therefore, the maximum uplink data rate is 960 kbps. Unique scrambling codes are used to separate users on the uplink. OVSF codes can not be used for this purpose, since the uplink transmissions from different users are not synchronized. OVSF codes are used on the uplink to separate streams of data for a single user. WCDMA also uses a variable channel coding scheme to provide differentiated QoS. Standard traffic can be sent with no channel coding. Convolutional codes with coding rates of 1/3 to 1/2 are used for traffic with BER of 10^{-3} [42]. Additional Reed-Solomon outer coding can be added for BER requirements of 10^{-6}. In addition to these channel codes, interleaving is applied to minimize the effects of burst errors. The combination of data rate, FEC, interleaving, and multiplexing of user streams is termed a Transport Format Combination (TFC). The WCDMA physical layer provides information transfer services to the MAC and higher layers. The services provided by the physical layer are termed transport channels.

The following transport channels [43] are defined.

- Random Access Channel (RACH): A contention-based uplink channel used for transmission of relatively small amounts of data.
- Common Packet Channel (CPCH): A contention-based channel used for transmission of bursty data traffic in the uplink FDD mode.
- Forward Access Channel (FACH): A common downlink channel used for transmission of relatively small amounts of data.
- Downlink Shared Channel (DSCH): A downlink channel shared by several UEs carrying dedicated control or traffic data.
- Uplink Shared Channel (USCH): An uplink channel shared by several UEs carrying dedicated control or data traffic in the TDD mode.
- Broadcast Channel (BCH): A downlink channel used for broadcast of system information in an entire cell.
- Paging Channel (PCH): a downlink channel used to broadcast control information to an entire cell, allowing efficient UE sleep mode procedures.

- Dedicated Channel (DCH): A channel dedicated to one UE in the uplink or downlink.
- Fast Uplink Signalling Channel (FAUSCH): An uplink channel used to allocate dedicated channels in conjunction with FACH.

2.1.2 Medium Access Control (MAC) layer

The MAC layer provides unacknowledged transfer of data units. The functions of the MAC layer include selection of an appropriate TFC, multiplexing of user streams on transport channels, and resolving contention and access for shared channels. The MAC layer is also responsible for reallocating physical layer resources based upon direction from the RRC. The MAC layer provides logical channels to the RLC and higher layers, which are mapped onto the physical layer transport channels. The MAC logical channels are classified as either control channels or traffic channels, which provide services to the control plane and user plane respectively. The following logical channels are defined.

- Broadcast Control Channel (BCCH): A downlink channel for broadcasting system information.
- Paging Control Channel (PCCH): A downlink channel used to send paging information when the network does not know the location of the UE, or when the UE is in the sleep mode.
- Common Control Channel (CCCH): A bidirectional channel for transmitting control information between the network and UEs. This channel is used for UEs with no dedicated connection.
- Dedicated Control Channel (DCCH): A bidirectional channel for transmitting control information between the network and a single UE.
- Dedicated Traffic Channel (DTCH): A point-to-point dedicated channel for the transfer of user information between one UE and the network. A DTCH can exist in both the uplink and the downlink.
- Common Traffic Channel (CTCH): A point-to-multipoint unidirectional channel for the transfer of user information to a set of dedicated UEs.

2.1.3 Radio Link Control (RLC) Layer

The RLC is responsible for the establishment and release of a Layer 2 connection. The functions performed by the RLC include segmentation and assembly, error correction by retransmission, flow control, duplicate detection, and in sequence delivery of higher layer Packet Data Units (PDUs). The RLC provides three data transfer modes to higher layers.

- Transparent Data Transfer. This service transfers higher layer PDUs with no additional protocols except segmentation and reassembly.
- Unacknowledged Data Transfer. This service transfers higher layer PDUs without guaranteeing delivery. In this mode, the RLC does not guarantee that packets will arrive in sequence or at all. Unacknowledged data transfer will not deliver duplicate packets or packets with errors.
- Acknowledged Data Transfer. This service provides reliable data transfer to higher layers. The RLC guarantees that packets will arrive error free, in sequence, with no duplicates. An option that allows out of sequence delivery is also available.

2.1.4 Radio Resource Control (RRC) Layer

The RRC layer handles control plane signalling between the UE and UTRAN. The RRC functions include the assignment, reconfiguration, and release of radio resources. This includes code allocation, admission control, handoff, and UE monitoring. The RRC is also responsible for controlling the requested quality of service. The RRC offers broadcast control services to the core network.

2.2 WCDMA physical channel structure

WCDMA defines two types of dedicated physical channels discussed in the following section.

2.2.1 Uplink DPDCH and DPCCH

In the uplink, the DPDCH and DPCCH are code and IQ multiplexed within each radio frame. The uplink DPDCH carries layer 2 data, while the DPCCH carries pilot bits, transmit-power-control (TPC) commands, an optional transport format combination indicator (TFCI) and feedback information (FBI) bits. FBI bits are used when closed form diversity is used in the downlink. A certain TFCI defines how the layer 2 data carried on the DPDCH('s) is multiplexed and coded and what spreading factor is used, etc. The TFCI informs the receiver side what TFC is used in the current data frame in order to simplify detection, decoding, and demultiplexing. For “simpler” services, blind-rate detection can be done in the receiver, and the TFCI is then left out. The uplink

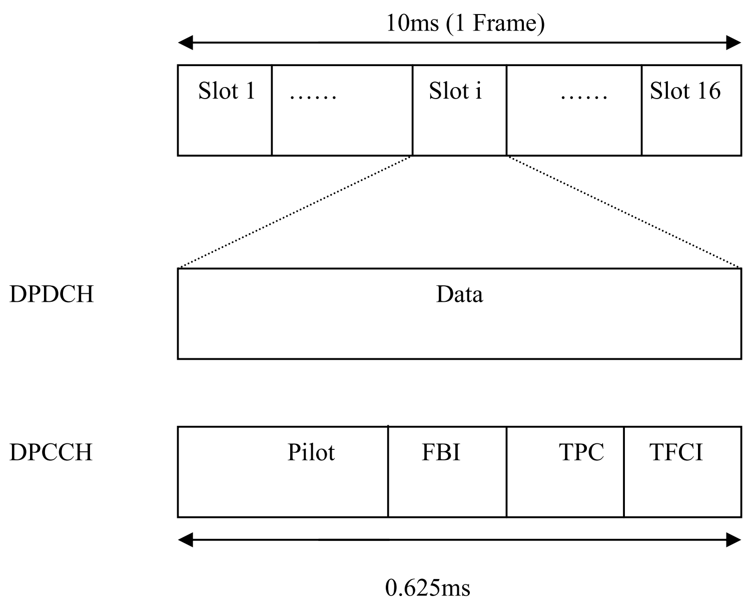


Figure 2.5 Uplink DPDCH/DPCCH frame structure

DPDCH and DPCCH are shown in Figure 2.5. Each frame of length 10 ms is divided into 16 slots of length 0.625 ms, each corresponding to one power-control period. Hence, the power-control frequency is 1600 Hz. Within each slot, the DPDCH and DPCCH are transmitted in parallel on the in-phase (I) and quadrature-phase (Q) branches, respectively, using different codes. The spreading factors for the DPDCH and DPCCH can vary between 4–256, $SF=256/2^k$, $k=0,1,\ldots 6$. The DPDCH and DPCCH use different codes and can be of different rates. Hence, the spreading factor will, in general, differ between the two channels. To control the amount of overhead, the relative power between the DPCCH and DPDCH can be varied. Typical values for the relative power difference are 3 and 10 dB for speech and 384-kbps data, respectively. Spreading and modulation of the uplink dedicated physical channels is shown in Figure 2.6. The DPDCH and DPCCH are mapped to the I and Q branch, respectively, and spread to the chip rate with two different channelization codes. The resulting complex signal is scrambled, and QPSK modulation with rootraised cosine pulse shaping with a rolloff factor of 0.22 in the frequency domain is applied. When multicode transmission is used, additional DPDCH's are mapped to either the I or Q branch. For each branch, each additional DPDCH is assigned a new channelization code. The channelization codes are

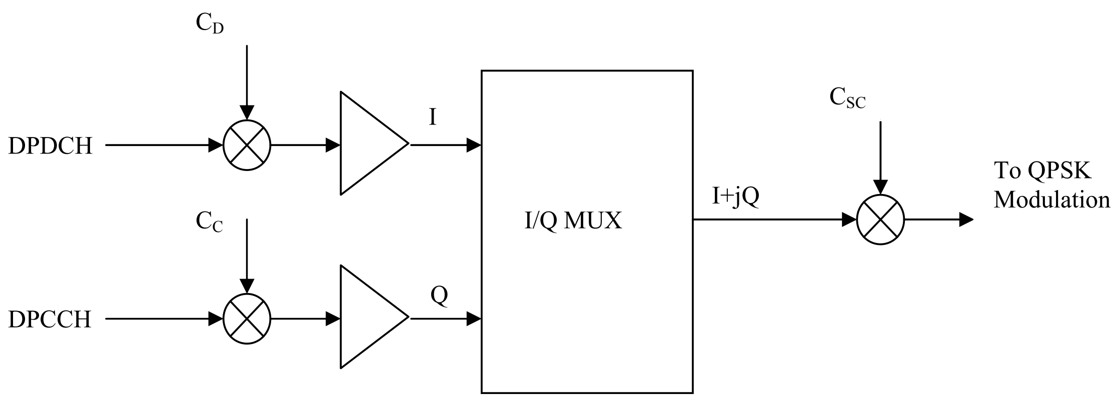


Figure 2.6 Uplink channelization and scrambling. Channelization codes are C_C and C_D and scrambling code is C_{SC}

used to spread the data to the chip rate, preserving orthogonality between physical channels with different rates and spreading factors. So-called orthogonal variable spreading factor (OVSF) codes are used for the channelization. Each level in the code tree corresponds to a certain spreading factor. A physical channel spread by the code is orthogonal to another physical channel spread by if and only if is not on the path to the root of the tree from or in the subtree below. Hence, the number of available codes is not fixed, but depends on the rate and spreading factor of each physical channel. The uplink scrambling code can be either short or long. The short scrambling code is a complex code built of two 256-chips-long extended codes from the VL-Kasami set of length 255. The long scrambling code is a 40960-chips segment of a Gold code of length 2^{41}-1. Both channelization codes and UE-specific scrambling codes are assigned by the network. The set of channelization codes used may be changed during the connection. Cells using advanced receivers, e.g., multiuser detection, will typically use the short scrambling code to lower the complexity of the receiver algorithm. When short codes are used, the cross-correlation properties are maintained between symbols, making, e.g., the updating of a cross-correlation matrix less complex. However, short codes have worse interference averaging properties than long codes. Hence, in cells where, e.g., an ordinary RAKE receiver is used, the long scrambling code is used. The IQ multiplexing of control and data is used to ensure that electromagnetic compatibility (EMC) problems are minimized in the UE. To minimize interference and maximizing capacity, during speech silent periods no data is transmitted. However, pilot bits and power-control commands are needed to keep the link synchronized and power controlled. The IQ multiplexing avoids pulsing the power with a given frequency. If time multiplexing of control and data was used instead, a 1600-Hz tone [44] would be emitted during silent periods.

2.2.2 Downlink DPDCH and DPCCH

In the downlink, the DPDCH and DPCCH are time multiplexed within each radio frame. As in the uplink, the downlink DPDCH contains layer 2 data, while the DPCCH carries pilot bits, TPC commands, and an optional TFCI (see Figure 2.7). Similar to the uplink,

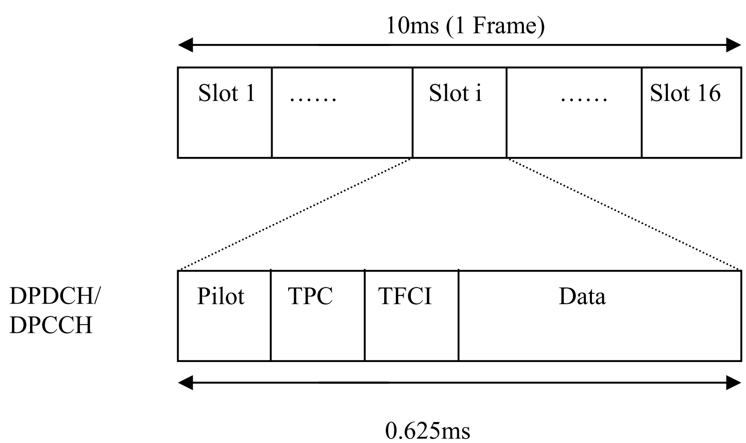


Figure 2.7 Downlink DPDCH/DPCCH frame structure

each frame of length 10ms is divided into 16 slots of length 0.625 ms, each corresponding to one power-control period. Within each slot, the DPCCH and DPDCH are time multiplexed and transmitted with the same code on both the I and Q branches. The spreading factor for the DPDCH and DPCCH can vary between 4–512, SF=$512/2^k$, k=0,1,…7. Figure 2.8 shows the spreading and modulation of the downlink dedicated physical channels. The DPCCH/DPDCH bits are mapped in pairs to the I and Q branches, and spreading to the chip rate is done with the same channelization code on both I and Q branches. Subsequent scrambling is then performed before QPSK modulating the complex signal. Rootraised cosine pulse shaping with a rolloff factor of 0.22 in the frequency domain is used. Channelization is done using the same type of

OVSF codes as for the uplink dedicated physical channels, and the set of codes used can be changed by the network during a connection. The downlink scrambling code is a 40960 chips segment of a Gold code of length 2^{18} -1. There are 512 different segments

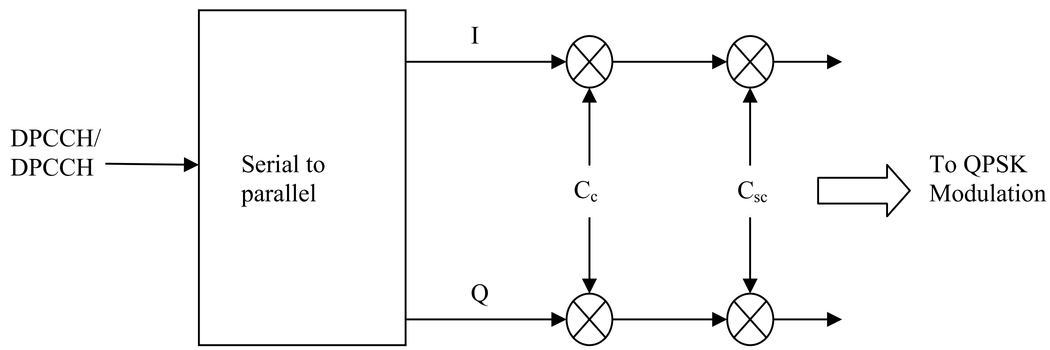
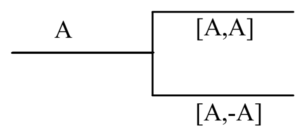


Figure 2.8 Downlink channelization and scrambling. Channelization codes is C_{Ch} and scrambling code is C_{SC}

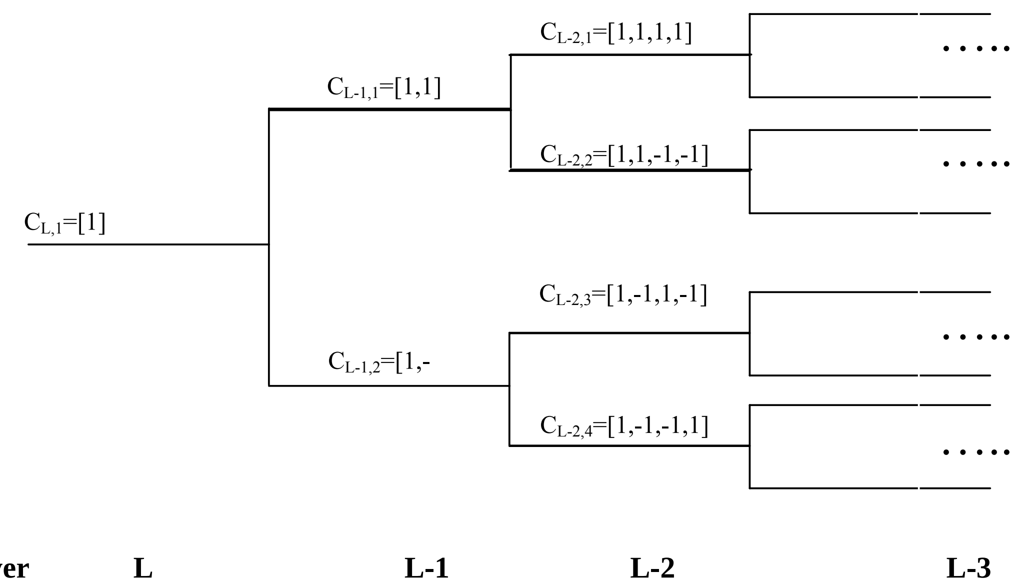
used for downlink scrambling. These are divided into 16 groups of 32 codes each in order to simplify the cell-search procedure (see further initial cell search in Section IV-C). Each cell is assigned a specific downlink scrambling code at initial deployment. For multicode transmission, each additional DPCCH/DPDCH is spread and scrambled in a similar way using a channelization code that keeps the physical channels orthogonal. Contrary to the uplink, time multiplexing of control and data does not lead to EMC problems in the downlink. Taking into account the fact that all users share the channelization codes in the downlink, the IQ multiplexing scheme where a whole code is needed for the DPCCH only will use unnecessarily many codes. Hence, time multiplexing is a logical choice in the downlink. The use of pilot bits on the WCDMA dedicated physical channels ensures that adaptive antennas can be introduced in the downlink. If a common downlink pilot signal is used for coherent detection, like in IS-95, that pilot must have the same antenna diagram as the traffic channel. This prohibits the use of downlink beamforming, where the traffic channels are transmitted in narrow beams.

2.3 OVSF code tree

In WCDMA, OVSF code tree is available with each BS and UE. Code tree provides the facility to transmit at different rates. The OVSF code tree generation is explained in



(a)

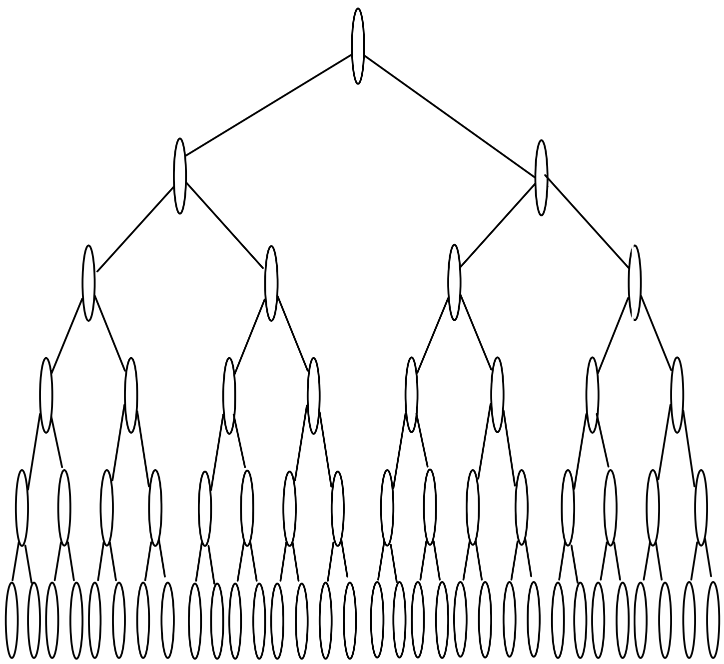


(b)

Figure 2.9(a) Walsh procedure to produce two orthogonal codes from a code [A]. Figure 2.9(b) Generation of OVSF code tree using Walsh procedure and with root $C_{L,1}$=[1].

Figure 2.9. For a code *A*, the two children are [*A*,*A*] (say code *B*) and [*A*,-*A*] (say code *C*). The code *B* produces two children [*B*,*B*] and [*B*,-*B*] and code *C* produces two children [*C*,*C*] and [*C*,-*C*]. This is according to the standard Walsh procedure. In WCDMA system, the procedure is repeated eight times to get 8 layer code tree. The layer numbering is done from leaves to root as 1 to 8. the SF in the layer l, $l \in [1,8]$ is 2^{10-l}. The number of codes in layer l is 2^{10-l}. As discussed earlier, the SF in WCDMA system downlink varies from 4,8,…512. In our thesis we consider SF varying from 1,2,…128

instead of 4,8,…512 for mathematical simplicity. The code in layer l is represented by $C_{l,n}$, where l is the layer number and n is the branch number in layer l. The value of n in layer l, $l \in [1,8]$ varies from 1 to 2^{8-l}. Also the SF of layer l is 2^{8-l}. The data rate handled



Layer	SF	Data Rate
6	1	32R
5	2	16R
4	4	8R
3	8	4R
2	16	2R
1	32	1R

Figure 2.10 Six layer OVSF code tree

by the code in layer l is 2^{8-l}R (R is 7.5 kbps). Therefore there are 8 quantized (in the form of 2^nR, $n \in [0,7]$)user rates are possible. The rates not in the form of 2^nR are called non-quantized data rates. Figure 2.10 shows the 6 layer OVSF code tree with maximum capacity of 32R. The full 8 layer code tree is not shown due to space constraint. The code tree shown can handle four six data rates R, 2R,…., 32R. In the OVSF scheme, a code can be given to the coming user if, all descendents and ancestors of the code from root to leaf are free. Accordingly, only one code can be assigned to a UE in the path from the root to leaf. The code with the smaller SF can be used for user with relatively higher data rate so that the overall bandwidth of the system is same (equal to 3.84 Mcps). The relationship between user data, SF of the code and channel data is illustrated in Figure

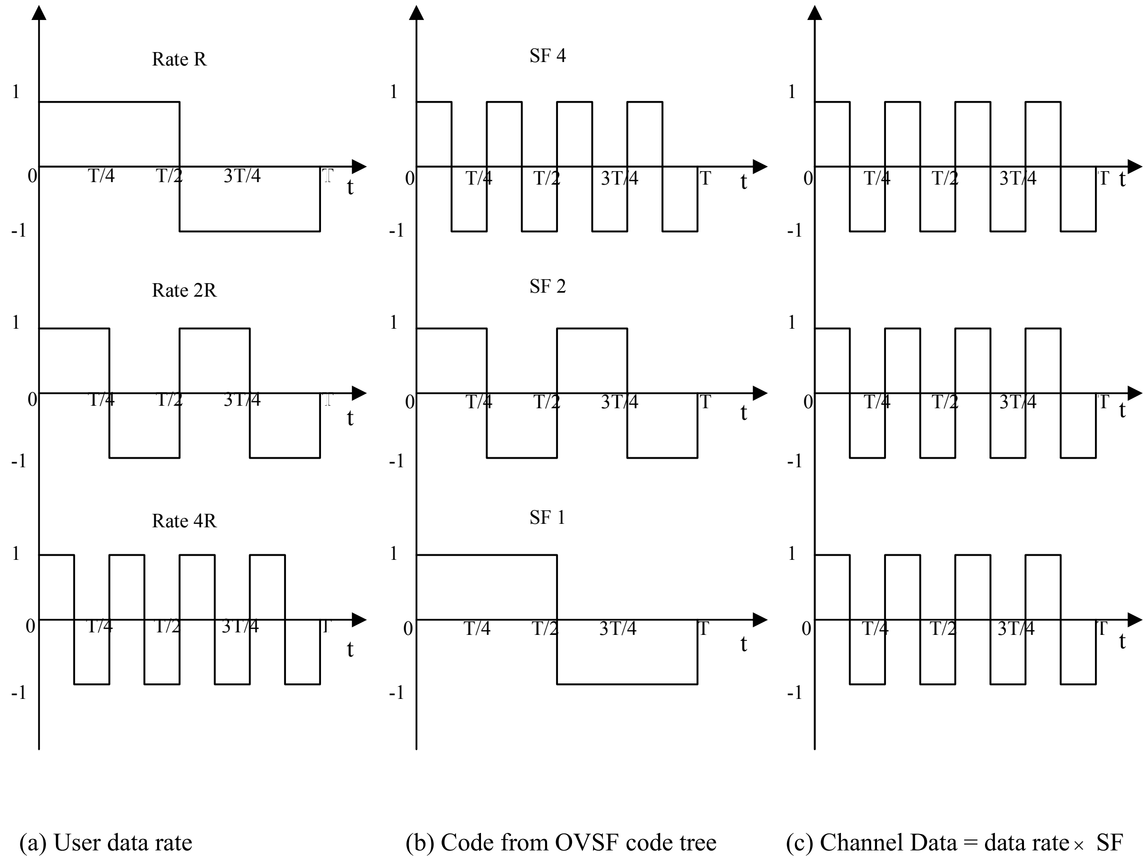


Figure 2.11 Relationship between user data rate, spreading codes and the channel data rate for three users with rates R, 2R and 4R. The spreading factors are normalized w.r.t. 4.

2.11 for three users with data rate R, 2R and 4R. The code SFs are 4, 2 and 1 making overall bandwidth equal to 4R for all three signals.

2.4 Code blocking

As explained earlier, code blocking is the major drawback of OVSF-CDMA system. According to definition, a new call can not be supported even if the system has enough capacity to handle it. There are three possible statuses of the codes given below

- *Busy code*. A code occupied by the call.
- *Blocked code*. A code blocked due to busy child or parent.
- *Vacant code*. A unused code in the code tree.

Table 2.1 Codes blocked for busy code $C_{l,n}$

Layer	Codes Blocked
8	$C_{8,\left\lceil \frac{n}{2^{8-l}} \right\rceil}$
7	$C_{7,\left\lceil \frac{n}{2^{7-l}} \right\rceil}$
………	………..
l+1	$C_{l+1,\left\lceil \frac{n}{2} \right\rceil}$
l-1	$C_{l-1,2^1-1}$ to $C_{l-1,2^1}$
l-2	$C_{l-2,2^2-1}$ to $C_{l-2,2^2}$
………..	………..
1	$C_{l,2^{l-1}n-2^{l-1}+1}$ to $C_{l,2^{l-1}n}$

When a code $C_{l,n}$ is occupied by an user, the ancestors and descendants blocked are given in Table 2.1. In Figure 2.12, the code tree with four layers is considered. The maximum

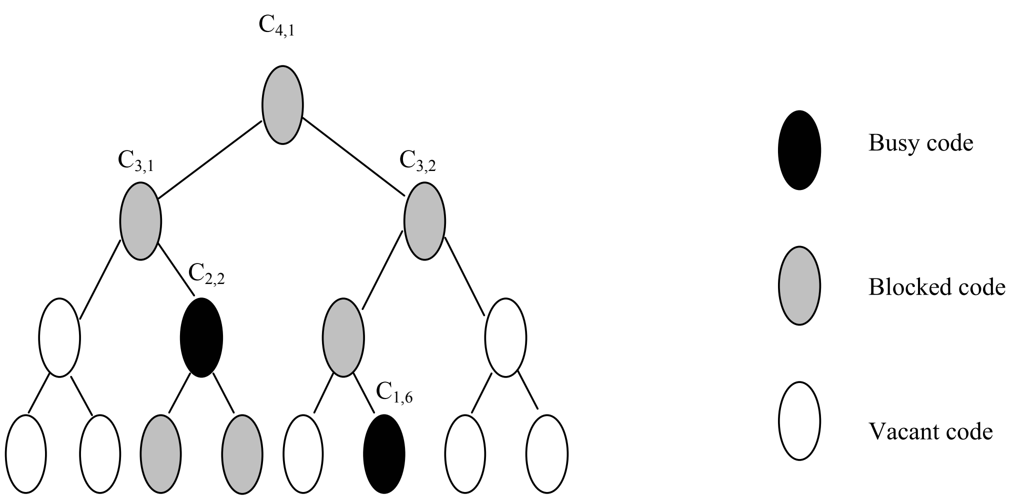


Figure 2.12 OVSF code blocking

capacity of the code tree is 8R. In the code tree, two codes with spreading factor 4 (for data rate 2R) and 8(for data rate R) are occupied. So, the capacity used for the code tree is 3R. The remaining capacity of the tree is 5R. If a new call with data rate 4R arrives, code from the third layer is required. The code tree is not able to provide code for the new call because both the codes corresponding to 4R capacity are blocked. This is called code (call) blocking and can be avoided using efficient assignment and reassignment schemes.

2.5 Internal fragmentation and external fragmentation

As explained earlier, the code capacities in the code tree are quantized. If a new call with the rate kR, $k \neq 2^n$ arrives, there is no code with the capacity kR. The call uses a code with capacity 2^mR, $2^{m-1}<k<2^m$. The code capacity (2^m-k)R is not used by the call and is wasted. This is called internal fragmentation problem. The gap 2^m-k increases as we go up in the code tree and may reach comparable to kR. So the high non-quantized data rates are over served by quantized code capacity. To illustrate internal fragmentation, a call requiring a rate of 9R may be given a 16R code. The wasted capacity is 7R equal to 44%. The internal fragmentation problem is discussed in [21,45].

To reduce the internal fragmentation problem and better utilize the scarce wireless bandwidth, one possibility is to use multiple (smaller) OVSF codes to support a call. For example, a call requesting rate 9R can be supported by a 1R code and an 8R code. This direction has been explored in [46,47]. The use of multiple codes for single call increases hardware complexity. In addition to the internal fragmentation problem, while connections are arriving and leaving the system, an OVSF code tree may become too fragmented to support newly arrived calls even if there are sufficient spaces in the code tree. This is referred to as the external fragmentation problem. Solutions to this problem require intelligent code assignment and code reassignment strategies. The former addresses how to assign code(s) to a new call in the code tree to avoid the tree becoming too fragmented. The latter addresses how to relocate code(s) when a new call arrival finds it difficult to get a vacant code in enough remaining capacity scenario [13]. Code reassignment involves costs, which should be minimized. This is very similar to the traditional memory management problem in operating system design [18]. Efficient code assignment and reassignments have significant impact on bandwidth utilization and call blocking probability.

2.6 OVSF code assignment schemes

As mentioned earlier, the performance of OVSF-CDMA can be improved using efficient code assignment and reassignment schemes. These schemes can be arranged in any of the following categories

2.6.1 Static code assignment schemes

The static code assignment schemes [48,49] rely on efficient placement of the code for the new call such the available capacity of the tree is better utilized. The code selection criterion is to such that the code tree is least fragmented. This leads to less code scattering and hence the number of vacant codes for higher rate calls increases.

2.6.2 Dynamic code assignment schemes

The dynamic code assignment schemes [50-54] do code reassignments/replacements to reduce the code blocking. The criterion to choose reassignments depends upon the cost of reassignments as explained in [50]. The reassignments increase the cost and complexity at the transceiver part.

2.6.3 Single code assignment schemes

The single code assignment schemes [55,56] use only one code from the OVSF code tree. The single code usage requires single rake combiner in the BS and UE. Some of the single code assignment schemes are explained below.

2.6.3.1 Leftmost Code Assignment (LCA) scheme

In LCA [60] scheme, availability of code is checked from the left side of code tree. If code of required rate is available, it is assigned to the call. If code is not available, call is rejected. LCA scheme is simple and do not require reassignments. The scheme is useful when amount of traffic is limited. The scheme suffers from large call/code blocking.

2.6.3.2 Random Assignment (RA) Scheme

In RA [60] scheme, any of the vacant code is picked randomly from the code tree. If code is not available, call is rejected. The code blocking in RA scheme is high making it useful for limited traffic as in the case of LCA.

2.6.3.3 Crowded First Assignment (CFA) scheme

In crowded first [60] code assignment scheme, the code availability is checked from the crowded portion of the tree. The benefit is increase in number of higher data rate vacant codes. The assignment scheme is compact in the sense that the vacant capacity in not too fragmented. The CFA scheme produce less code blocking compared to RA and LCA schemes. The complexity of the scheme is more compared to LCA and RA because of continuous check for the statuses of existing codes/calls at every new arrival. The CFA scheme can be used for medium to high traffic load conditions.

2.6.3.4 Class Partition Assignment (CPA) scheme

In CPA scheme the code tree is divided into L, L<8 number of groups. Each of the L groups is assigned to one of the arrival rate classes. The number of codes in each group depends upon the data rate of the classes. Figure 2.13 shows the illustration of

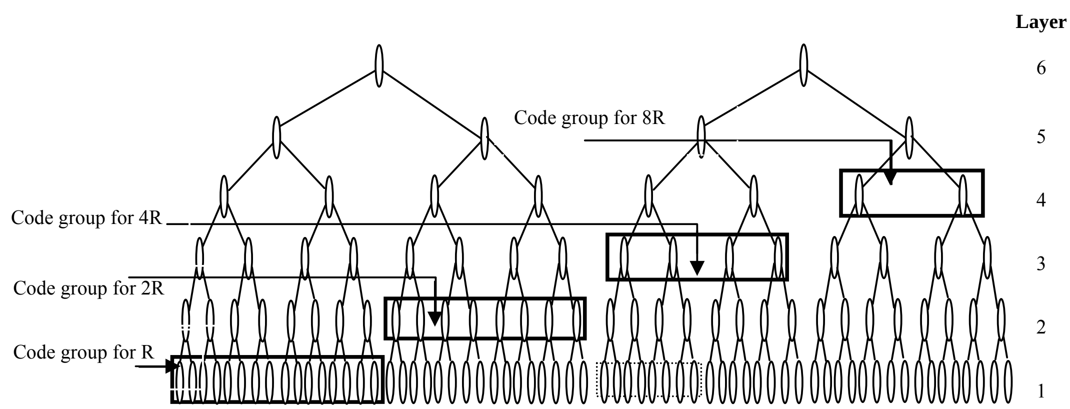


Figure 2.13 Illustration of CPA scheme

CPA scheme. We consider 6 layer codetree to handle four different classes R, 2R, 4R and 8R. There are four groups with number of codes in layer l, $l \in [1,4]$ are 2^{5-l}. The codes in the four groups are shown by rectangles in Figure 2.13. The distribution is uniform in terms of capacity of each group and is exponential in terms of number of codes. The capacity of each group in the Figure 2.13 is 16R. We can extend the code tree for 8 layers. The major benefit of the CPA scheme is less number of codes searched for new incoming call. The obvious limitation of CPA scheme is large code blocking and smaller throughput. The CPA scheme is also called Fixed Code Partitioning (FCP) scheme or Fixed Set Partitioning (FSP) scheme. The code assignment schemes similar to the CPA scheme are given in [61,62].

2.6.3.5 Dynamic Code Assignment (DCA) scheme

The DCA scheme is the most useful single code assignment scheme in terms of producing least amount of code blocking. When a new call arrives, availability of code is checked similar to LCA/RA/CFA scheme. If code is available it is assigned to new call. The fundamental principal is "if the vacant code is not available and net capacity is

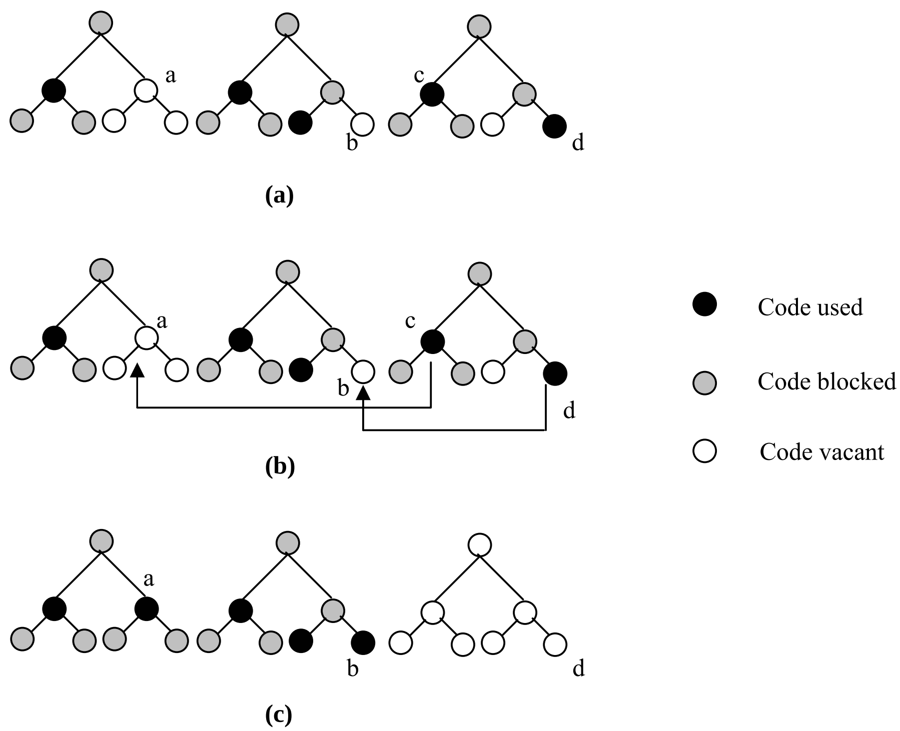


Figure 2.14(a) Status of available codes before arrival of 4*R* user (b) Shifting of codes using DCA scheme (c) Vacant 4*R* code ready to handle 4*R* user

within the maximum capacity, the call can be handled by reassignments of busy codes". To make code assignment optimal, the cost is checked for every blocked code with rate equal to rate of incoming call. The code with minimum cost is picked. One of the parameters of cost can be number of codes reassigned. All the descendants of minimum cost code are reassigned to other branches and code becomes vacant. Lesser is the number of code reassigned, less is the amount of overhead required to send the information of the reassignments. This vacant code can be assigned to the coming call. The other parameters of the cost are given in [50]. The signaling overhead increases proportional to the number of reassignments. The DCA scheme is explained using Figure 2.14. We take a code tree which can handle three different data rates R, 2R and 4R. The capacity of the system is 12R out of which 8R capacity is in use due to five users. Initially, the codes are assigned according to leftmost code first strategy. If a user with data rate 4R arrives, system is unable to handle data rate due to unavailabilty of vacant codes as shown in the Figure 2.14(a). If we apply proposed code reassignment strategy, we shift users with code *c* and *d* to code *a* and *b* as shown in Figure 2.14(b). After these reassignments, we left with vacant 4*R* code in third tree. This code can be assigned to the 4R user. The similar schemes are discussed in [50-54]. So, the code blocking is less in dynamic code assignment at the cost of extra control overhead required to send the information of code reassignments to the UE and BS.

2.6.3.6 Ancestor Cost Assignment (ACA) scheme

The scheme is also called as compact assignment scheme, because the code trees are compact in terms of location of busy codes. The new call is always given code location so that the vacant codes for high rates in future are highest in number. No reassignments are required in ACA. It is one of the best assignment schemes in terms of having minimum blocking probability with no code reassignments. For a vacant code $C_{l,k}$ ancestor cost $AC_{l,k}^{l+1}$ is calculated, where $AC_{l,k}^{l+1}$ is the number of occupied descendant codes for the parent of code $C_{l,k}$ in layer l+1. All the vacant codes are checked for finding parent code with maximum number of descendants used. The vacant code with the highest ancestor cost is the candidate for new call. If tie occurs in the number of occupied descendants for codes in layer l+2, parents in layer l+3 are checked for occupied descendants. Procedure is continued till suitable parent is chosen. If tie is not resolved till the 8th layer any of the vacant codes in the tie is used for the new call. Some of the similar schemes are given in [63].

2.6.3.7 Class Partition Assignment and Reassignment (CPAR) scheme

The CPAR scheme reduces the blocking probability in CPA scheme. In this scheme, the total number of trees *T* (T is the number of trees in layer *l*, $1<l<8$) is divided into assign tree set (T_A) and reassigns tree set (T_R). The codes in the assign tree set are divided according to the arrival distribution as in the CPA scheme. No reassignments are done in the assign tree set codes. Codes in the reassign set can be used for all classes and can be assigned and reassigned. The reassignments are similar to reassignments in the DCA scheme. The number of codes searched is more as compared to CPA scheme. The example of CPAR scheme is [64].

2.6.4 Multi-code assignment schemes

The multi-code assignment scheme [57,58] uses multiple codes to handle non-quantized data rates. This requires multiple rake combiners equal to the number of codes in multi-code at the BS and UE, and hence the complexity is more. The hybrid code assignment scheme [59] combines single code use and multiple codes use for better performances.

Along with the above code assignment and reassignment schemes, some more assignment and reassignment strategies are given in literature. In the rotated single code assignment scheme [65], linear code chains (LCCs) and non-linear code trees (NCTs) are identified and the code assignment gives lesser blocking probability and reassignment cost. It uses the unsequence property of linear code chains to design a new code assignment and reassignment algorithm. The scheme initially attempts to allocate request code to LCCs and then tries to allocate them to NCTs. The code blocking is reduced along with the reassignment cost. The rotated single code assignment scheme is extended to multi-code rotated code assignment in [66]. The non-blocking OVSF codes [67-71] reduce the code blocking to zero. There are three categories of NOVSF codes with the properties given below.

1. Time multiplexing is used to divide the code usage time into slots. The slots of the code time can be used by one or more channels.
2. The OVSF codes are reorganized such that all the codes are orthogonal. The OVSF code trees with initial 4 or 8 codes are generated.
3. In the third category, the OVSF codes are generated such that there is no limit on the upper bound of SF.

The code assignment in [72] provides throughput improvement under constraints of transmitted power and bandwidth. The time based code assignment [73] scheme considers the impact of remaining time of the call in progress to improve the performance. The EOVSF (Extended OVSF) [74] codes provide more code candidates compared to the NOVSF codes. This gives better system utilization compared to the NOVSF codes. The multi-rate multi-code compact assignment (MMCA) [75] scheme uses the concept of compact index to accommodate QoS differentiated mobile terminals. MMCA has following important properties.

- MMCA does not perform code rearrangement and is therefore simple.
- MMCA provides priority differentiation between real time calls and data packets.
- MMCA supports mobile terminals with different multi-code transmission capabilities.
- MMCA balances transmission qualities among the multiple codes assigned to the same user.
- MMCA supports multi-rate real time calls and keeps the code tree as flexible as possible in accepting new multi-rate calls.

The maximally flexible assignment scheme [76] discusses two code assignments namely rearrangeable code assignment and non rearrangeable code assignment schemes. It define flexibility index to measure the capability of assignable code set. Both schemes provides the maximal flexibility for the code tree after each code assignments. The performance of fixed and dynamic code assignment schemes with blocking probability constraint is given in [77]. The throughput performance is proved to be better. Non-rearrangeable compact assignment (NCA)[78] make the code assignment compact so that the remaining assignable codes are most flexible to accommodate future multirate calls. The code assignment scheme proposed in [79], the code with the least number of parents blocked for a candidate code allocation is used for assignment. The code assignment scheme [63] works on the top of [79] with two additional tie solving criterion. The DCA scheme with different QoS requirements is given in [80]. The improvement in terms of lesser code blocking and better code utilization is also shown. The code assignment schemes which are specifically used for real time video transmission are discussed in [81-83].

2.7 Performance parameters of OVSF codes

Consider M service classes of calls arriving according to independent Poisson processes. Calls of class-k requests the transmission rate of $2^k R$ arrival at rate $\lambda_k, k = 0,1,2,...M-1$, where R is the basic data transmission rate and k indicates the service class corresponding to the transmission rate of $2^k R$. The call duration for all classes is assumed to be exponentially distributed with mean $1/\mu$. The traffic load requesting the transmission rate of k is defined as $\rho_k = \lambda_k / \mu$. We use G_k to denote the total number of codes in a group that supports the data rate of class *k*. There exists a finite number of codes, represented by $G = (G_0, G_1, ..., G_{M-1})$, that satisfies the maximum capacity constraint $G_0 + 2G_1 + 4G_2 + ... + 2^{M-1} G_{M-1} = C_{\max}$ where $C_{\max}$ is 128R. Each group of codes is uniquely assigned to one of the service classes. The blocking probability P_k of the code group corresponding to class-*k* can be computed using Erlang's formula [80]

$$P_K = \frac{\rho_k^{G_k} / G_k!}{\sum_{n=1}^{G_k} \rho_k / n!} \tag{2.3}$$

The average blocking probability $P_F(G)$ of the entire system with a fixed set partition $G = (G_0, G_1, ..., G_{M-1})$ becomes

$$P_F(G) = \sum_{k=0}^{M-1} \frac{\lambda_k}{\lambda} P_k \tag{2.4}$$

where $\lambda = \sum_{i=0}^{M-1} \lambda_i$. (2.5)

The average throughput of the system $\mathrm{T}_F(G)$ depends on the average code blocking is defined as

$$\mathrm{T}_F(G) = \sum_{k=0}^{M-1} (1 - P_k) \frac{\lambda_k}{\mu} (2^k R) \tag{2.6}$$

Therefore from Equation 2.6, the throughput increases with the decrease in the code blocking probability. The code utilization (U_c), of the OVSF-CDMA system is defined as the ratio of assigned bandwidth to the overall bandwidth of the system.

CHAPTER 3

Fast single code assignment schemes

3.1 Introduction

The number of codes searched in OVSF code tree is a measure of speed of the code assignment scheme. If the number of codes searched prior to finding a vacant code is large, the decision time is more and the new user waits for longer time to access code. The chapter proposes schemes to make code assignment decision time smaller.

3.2 Reserve Brother Assignment (RBA) scheme

3.2.1 Description

The code assignment scheme divide the OVSF code tree into T subtrees, where T=2^x, 0<x<L. When the incoming user requires a code from layer l, it is required to search only single code in each of the T sub trees. The scheme start searching vacant code $C_{l,x}$ from the left of the code tree. The number x varies from 1 to $2^{L-l}(T\text{-}1)+1$ with the difference of 2^{L-l} in the successive codes. When a code $C_{l,x}$ is used by new call, all the codes in the same tree are reserved for the future arrival of same rate users. The reservation of codes is valid when at least single code in the tree is occupied. When all the codes are vacant, same tree can be used to handle other rate users. The advantage of the proposed scheme is that it is adaptive to arrival class (rate) of users. There are four possible statuses of the codes as explained below.

Busy code. A code occupied by the user.

Blocked code. A code not orthogonal to the busy code in the same code tree.

Vacant code. A code orthogonal to the busy code.

Reserved code. A code orthogonal to the busy code in the same layer and belong to the same subtree in which busy code lies.

Let $C_{l,n}$ is the code occupied by the user. The codes blocked and reserved are listed in Equations 3.1-3.3.

Descendants Blocked

$$\begin{bmatrix} C_{l-1,2n-1}, C_{l-1,2n} & \text{layer } l\text{-1} \\ C_{l-2,4n-3}, C_{l-2,4n-2}, \ldots\ldots. C_{l-2,4n} & \text{layer } l\text{-2.} \\ & \\ . & \\ C_{1,n^{l-1}n-2^{l-1}+1}, C_{1,n^{l-1}n-2^{l-1}+2} \ldots\ldots. C_{1,2^n} & \text{layer 1} \end{bmatrix} \quad (3.1)$$

Ancestors Blocked

$$\begin{bmatrix} C_{l+1,\left\lceil \frac{n}{2} \right\rceil} & \text{layer } l+1 \\ C_{l+2,\left\lceil \frac{n}{4} \right\rceil} & \text{layer } l+2. \\ . & \\ C_{L,\left\lceil \frac{n}{2^{L-1}} \right\rceil} & \text{layer } L \end{bmatrix} \quad (3.2)$$

Codes Reserved

$C_{l,x}$, where x denote all the codes in the layer l corresponding to same code tree in which n lies (3.3)

Figure 3.1 show any code tree out of T subtrees in OVSF CDMA system. When the new user arrives, the first code in subtree needs to be checked. If code is either busy or

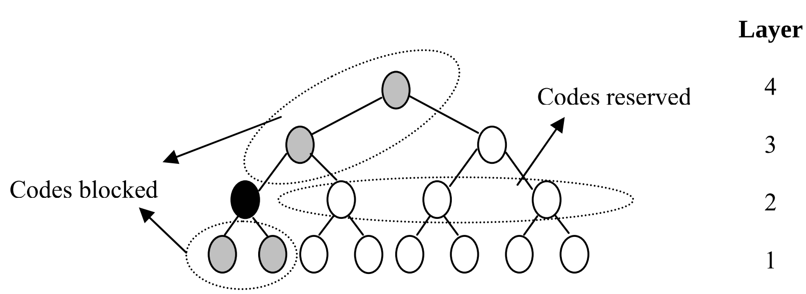


Figure 3.1 Codes reservation in RBA scheme

reserved, the appropriate vacant code lies within same tree. Otherwise go to the next tree and so on. Assume that initially the code tree is vacant. If a new user requires a code in the layer 2, code $C_{2,1}$ is assigned. The codes blocked and reserved are shown using different circles. In the Fixed Code Partition scheme [55,56], the number of codes checked depends on the partition set and rate of coming call. In FCP scheme, the number of codes checked increases exponentially as we go down to layer 1. In the proposed scheme, for any user maximum number of codes checked is independent of rate of

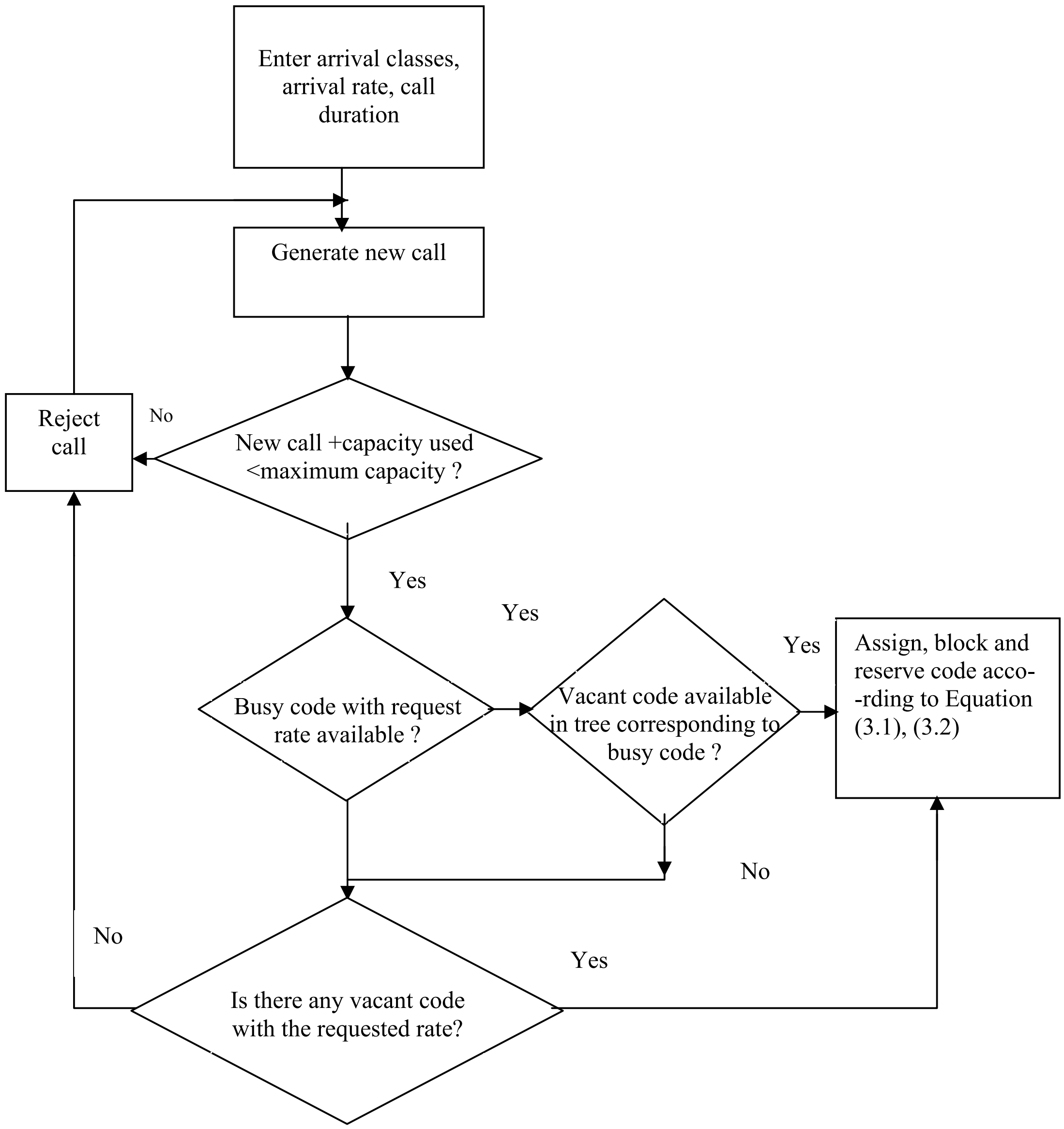


Figure 3.2 Flowchart for RBA scheme

coming user. Therefore the number of codes searched reduces exponentially compared to fixed partition scheme as we go down the tree. The number of codes checked is a measure of time required to decide for suitable code for new user.

3.2.2 Flowchart and algorithm

The flowchart of the assignment scheme is shown in Figure 3.2. The algorithm is outlined below

a. Enter arrival rate, service time, number of trees
b. Enter rate of new user
c. If available capacity is less than C_{max}, go to (d) else go to (h)
d. Check for availability of vacant code with rate of incoming call
e. If yes, go to the tree corresponding to busy code in step (d)
f. If vacant code is available, use it. Do code assignment, blocking and code reservation according to Equations 3.1-3.3.
g. If there is no vacant code or there is no busy code in (d), use vacant code from any of the tree and reserve all brothers of code used for same rate codes
h. If there is no vacant code in (g), call is discarded

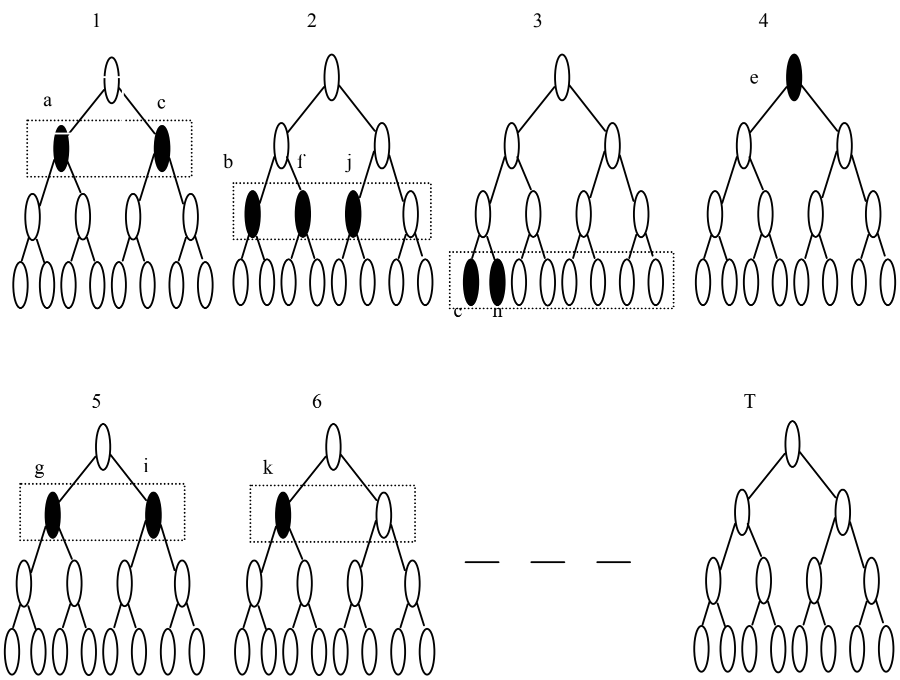


Figure 3.3 Illustration of code assignment in RBA scheme

According to the traffic conditions, there are two categories of RBA scheme.

- When the traffic is smooth, probability density function of the traffic remain uniform for longer time. Hence the tree partition does not change regularly and number of operations is small.

- When the traffic conditions vary rapidly, the tree partition is done frequently. The number of operations is more.

The assignment scheme is explained with the example in Figure 3.3. Consider an OVSF-CDMA system with four different classes of users with rate R, 2R, 4R and 8R so that there are 16 trees with roots in layer 4 (to make the maximum capacity equal to 128R, equal to the capacity of WCDMA system). Let the code trees are initially vacant and users arrives in pattern as 4R, 2R, 4R, 1R, 8R, 2R, 4R, 1R, 4R, 2R and 4R. Let us name the arrivals as a, b, c, d, e, f, g, h, i, j and k. The entries of events are shown in Figure 3.3. When the first user of rate 4R (a) comes, it is assigned a code from the layer3 $C_{3,1}$. Its ancestors and descendants are blocked. Its brothers in the same tree are reserved for future 4R calls. The next arrival is of rate 2R and is given code $C_{2,5}$. Its three brothers are reserved for future arrival of 2R calls. For the third arrival of 4R we go to the reserved code of 4R rate and assign it to the incoming call and so on.

3.3 Reserve Brother Reassignment (RBR) scheme

3.3.1 Description

In RBR scheme, the 8 layer OVSF code tree is divided into tree sets named assign tree set (T_A) and reassign tree set (T_B) as shown in Figure 3.4. The trees in assign tree set (T_A)

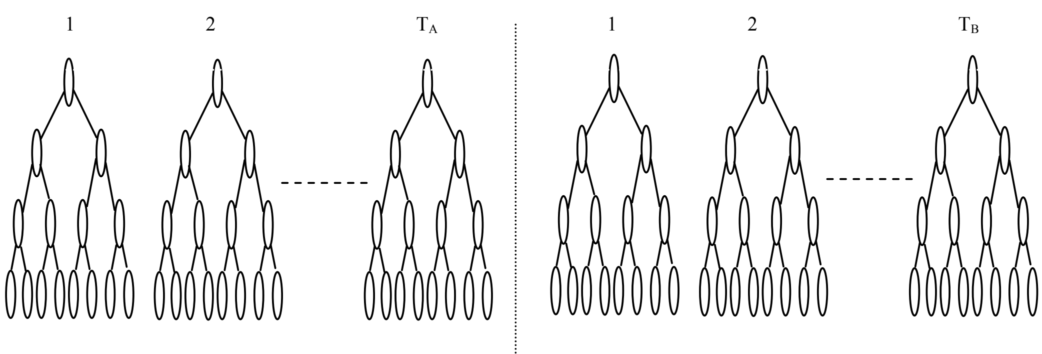


Figure 3.4 Division of trees in RBR scheme

are used only for assignment and codes are assigned according to assignment scheme proposed in section 3.1. If no vacant code is available, codes in the reassign tree set can be used. If directly no vacant code is available in reassign tree set also and required capacity is within the available capacity of the code trees, code reassignment may be done in the trees of reassign tree set. The reassignments are done according to DCA [44-48] scheme. The reassignment decreases the blocking probability of calls in the proposed assignment scheme. The transmission control overhead increases due to reassignments of codes.

3.3.2 Flowchart and algorithm

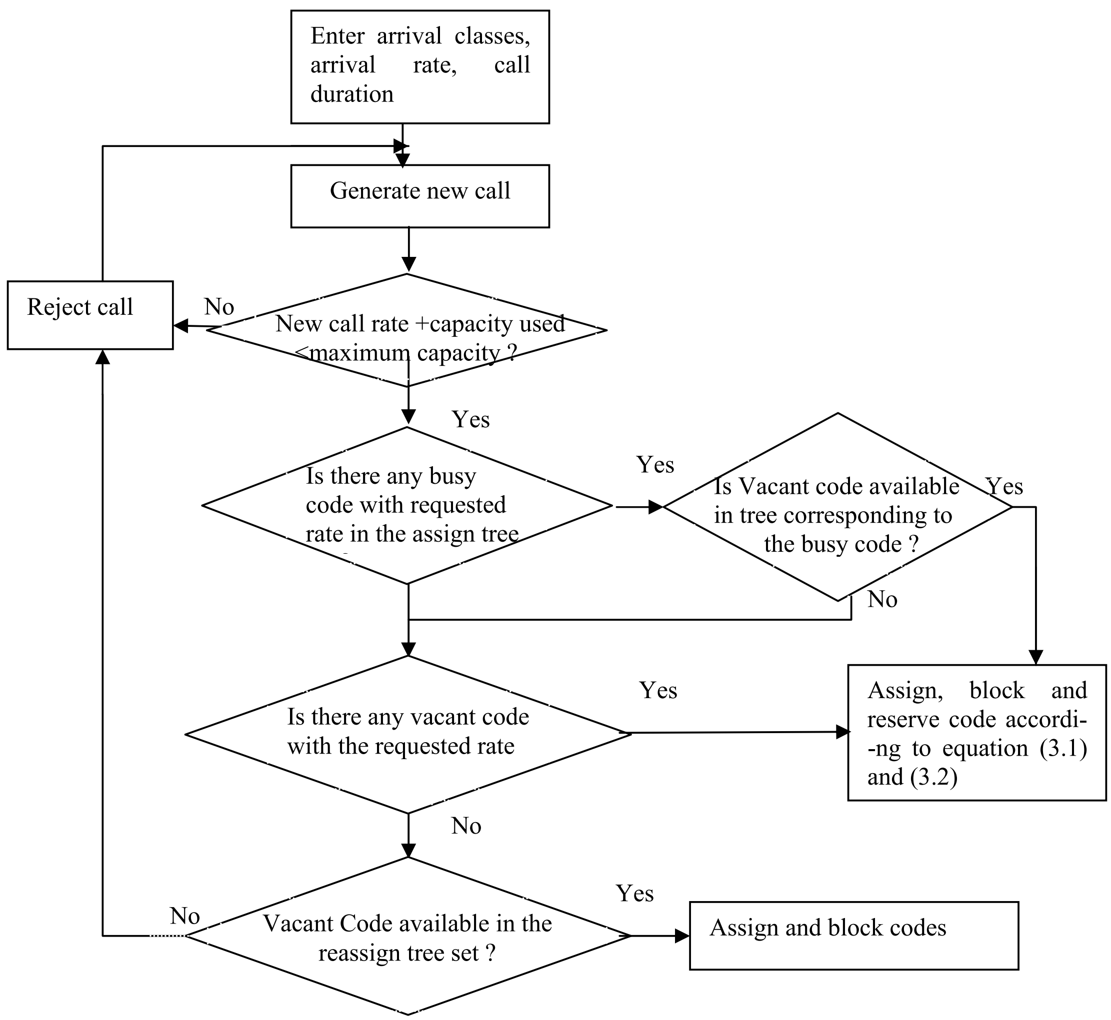


Figure 3.5 Flowchart for RBR scheme

The flowchart of the assignment scheme is shown in Figure 3.5. The algorithm is outlined below

a. Enter arrival rate, service time, number of trees

b. Enter rate of new user
c. If available capacity is less than C_{max}, go to (d) else go to (h)
d. Check whether any code of rate corresponding to rate of incoming is busy
e. If yes, go to the tree corresponding to busy code in step (d)
f. If vacant code is available, use it. Do code assignment, blocking and code reservation according to Equation 3.1-3.3.
g. If there is no vacant code or there is no busy code in (d), use vacant code from any of the tree in the assign tree set and reserve all brothers of code in the tree.
h. If there is no vacant code in the assign tree set, check the availability of vacant code in the reassign tree set. If vacant code is available, it is given to the incoming call. Block all the parents and children of the code.
i. If there is no vacant code in (h), call is discarded.

3.4 Assignment scheme adaptive to the tree properties (ATP)

3.4.1 Assignment scheme adaptive to the number of busy trees

The code reservation is done according to the trees vacant at the time of new user. Initially the trees are divided according to RBA scheme. The trees T are divided into two groups named T_1 and T_2. The tree set T_1 treats all calls in a similar way but T_2 is only

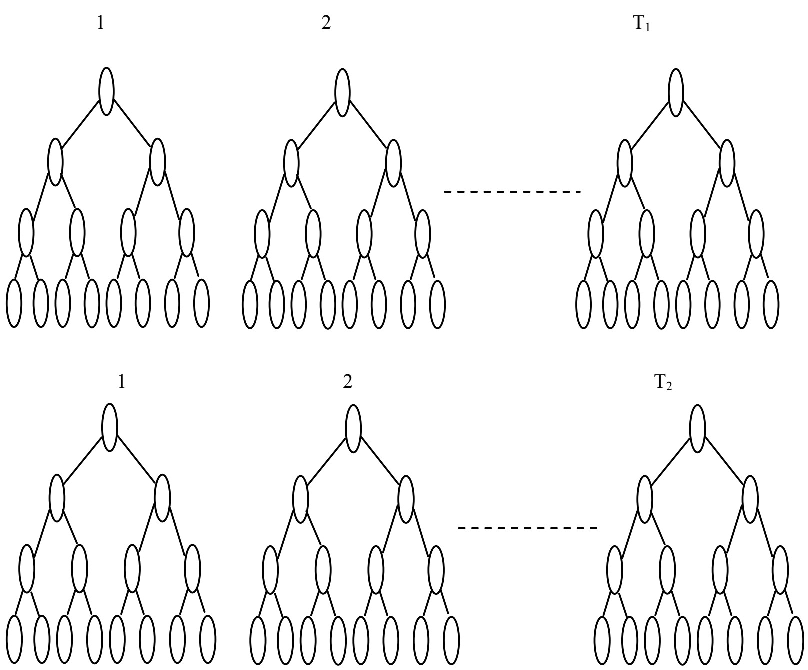


Figure 3.6 Adaptive assignment using number of trees

reserved for real time calls. So, higher is the distribution of lower rate calls, higher is the value of T_2. The division is shown in Figure 3.6. Hence, the threshold value (T_1) for number of trees can also be made variable according to the traffic conditions. This scheme provides reduction in call blocking compared to the RBA scheme.

3.4.2 Assignment scheme adaptive to the available capacity

In this scheme we put a threshold on the capacity used. If the capacity used exceeds the threshold value $C_{th}\{C_{th} < C_{\max}\}$, the higher data rate users are not accepted. Therefore the users of higher rate are accepted or rejected according to capacity used. We can vary the threshold according to the traffic conditions.

3.4.3 Assignment scheme adaptive to the available vacant codes

Consider the WCDMA system using four different traffic classes. The maximum number of vacant codes in the system is $G_0+G_1+G_2+G_3$, where G_x is the number of codes in the layer x. We set a threshold on G_2 and G_3 denoted as G_{2th} and $G_{3th.}$ When the threshold is reached the users of corresponding rates are not accepted. The requirement is to choose $\mathrm{G}^* = \{G_1, G_2, G_{3th}, G_{4th}\}$ so that average call blocking is minimized. The threshold can be made variable according to traffic conditions..

3.4.4 Input Parameters

- Call arrival process is Poisson with mean arrival rate, λ =0-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value, $1/\mu$ =1 units of time
- Possible OVSF code rates are R, $2R$, $4R$ and $8R$.
- Number of leaf codes are 128.
- Total number of trees is 16 with capacity of 8 units each making total capacity equal to 128 units.

3.4.5 Results

We compare the performance of RBA, RBR and ATP schemes with existing schemes LCA, DCA and FSP scheme discussed earlier. Let the probability distribution of

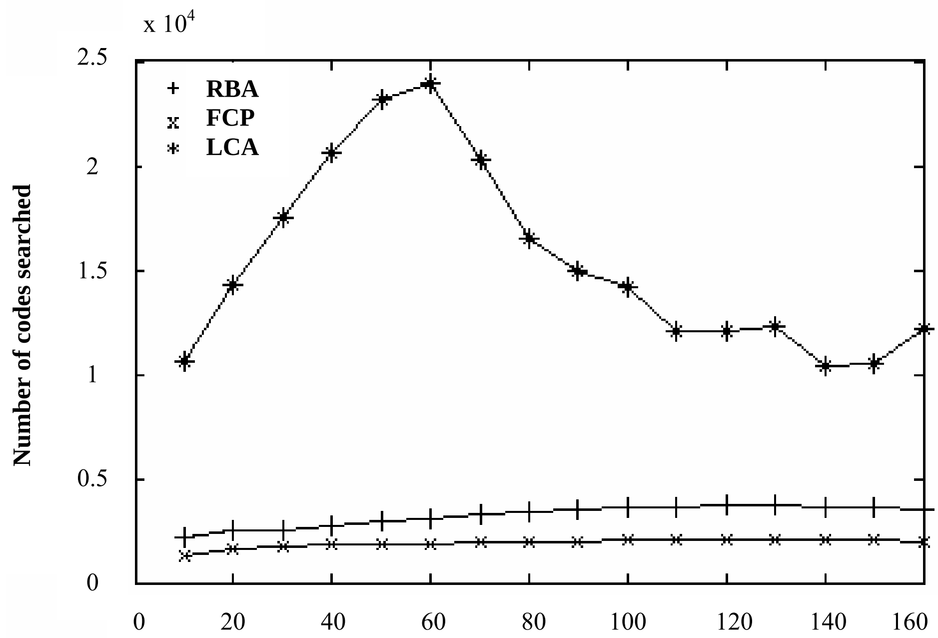


Figure 3.7 Number of codes searched for distribution [0.4,0.4,0.1,0.1]

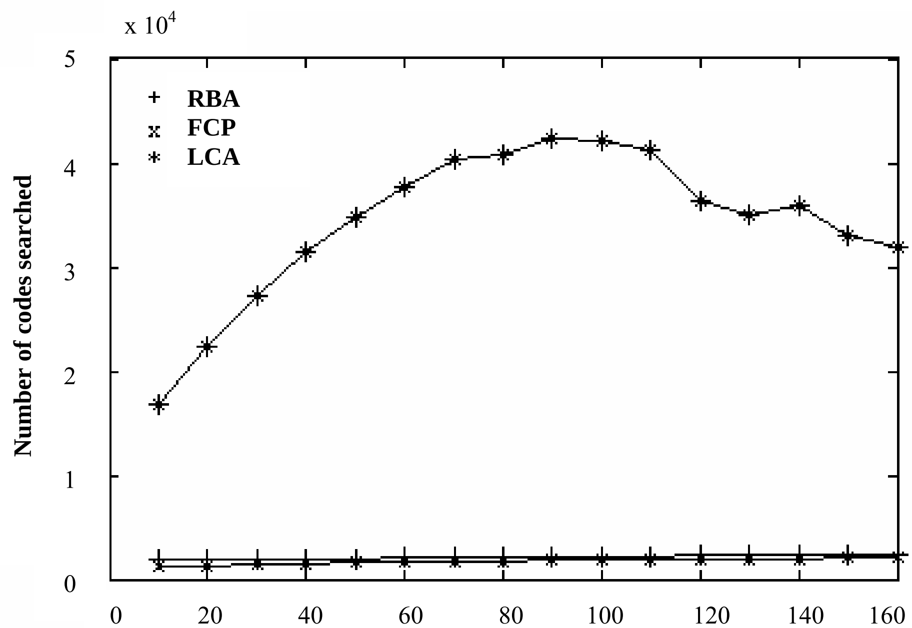


Figure 3.8 Number of codes searched for distribution [0.25,0.25,0.25,0.25]

different arrival classes are (p_1, p_2, p_4, p_8), where p_1,p_2,p_4 and p_8 are the probability of

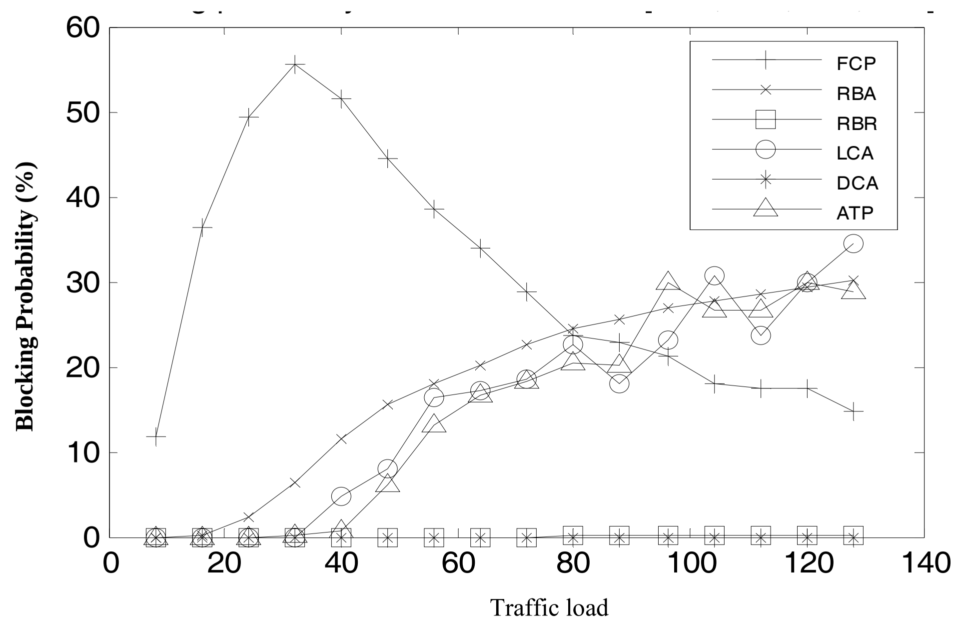


Figure 3.9 Blocking probability for distribution [0.4,0.4,0.1,0.1]

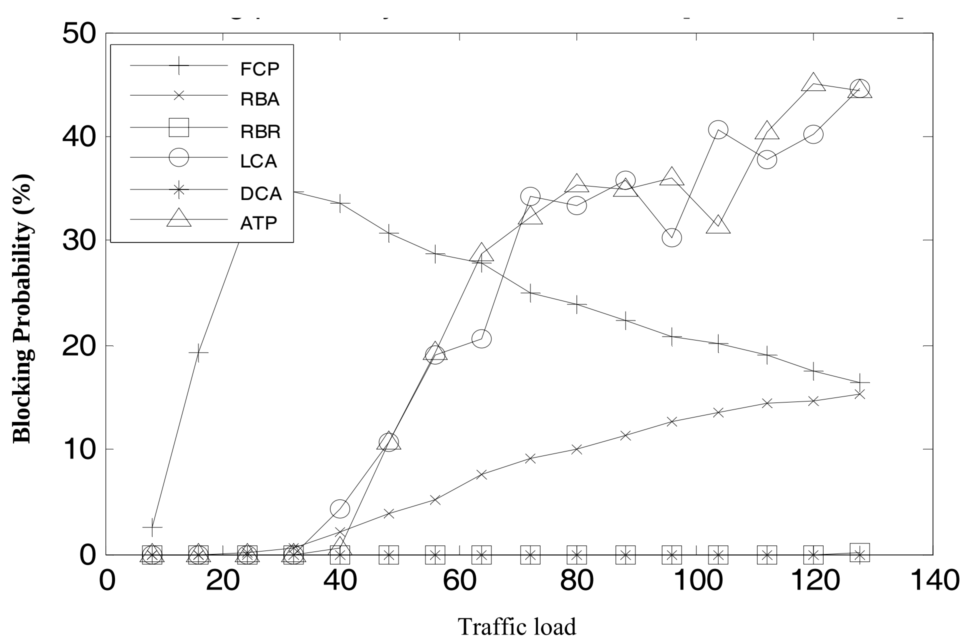


Figure 3.10 Blocking probability for distribution [0.25,0.25,0.25,0.25]

arrival classes corresponding to rate R, $2R$, $4R$ and $8R$. We consider two different distributions given by

- (0.1,0.1,0.4,0.4), when higher data rate classes dominates the traffic

- (0.25,0.25,0.25,0.25) ,when all the classes have same probability of occurrence

The number of codes searched is plotted in Figure 3.7 and Figure 3.8 showing benefit of RBA scheme compared to LCA and FCP schemes. The other schemes require even more codes to be searched than LCA scheme. So there is significant reduction in code searching in RBA scheme. The limitation of higher blocking in RBA scheme can be reduced in RBR scheme as shown in Figure 3.9 and Figure 3.10.

3.5 Fast Assignment (FA) scheme

3.5.1 Description

Consider an OVSF-CDMA system with T number of trees where each tree consists of L_1 (L_1<8) number of layers. Total number of codes in the system (G) is given by

$$\begin{aligned} G &= T + 2T + ... + 2^{L_1-1}T \\ &= T(1 + 2 + ... + 2^{L_1-1}) \\ &= T\sum_{k=0}^{L_1-1} 2^k = T(2^{L_1} - 1) \end{aligned} \tag{3.4}$$

These G codes are divided into total L_1 groups $G_1, G_1, ...G_{L_1}$ i.e $G_1 + G_2 + ...G_{L_1} = G$ and $G_x = T \times 2^{L_1-x}$, where G_x is the number of codes in layer x

Capacity of the system is given by

$$C_{\max} = T \times (2^{L_1-1}) \tag{3.5}$$

We assume that the call arrival pattern is $\lambda_1, \lambda_2, ...\lambda_{L_1}$ with probability of occurrence $1/2, 1/2^2, ..., 1/2^{L_1}$. All these codes should be orthogonal to each other irrespective of layer number.

For the arrival pattern given it is clear that incoming call distribution is such that all classes of codes share the bandwidth in equal proportion. So, on the average number of busy codes in layer x is G_x / L_1 where $x \in \{1,2,.....L_1\}$. In the fast assignment scheme total T trees are divided into two sets called *assign tree set* and *block tree set* as shown in Figure 3.11. The total number of trees in the *assign tree set* is $T_A = (T / L_1)$ and is chosen to accommodate average busy codes in all the layers for the mentioned distribution. So

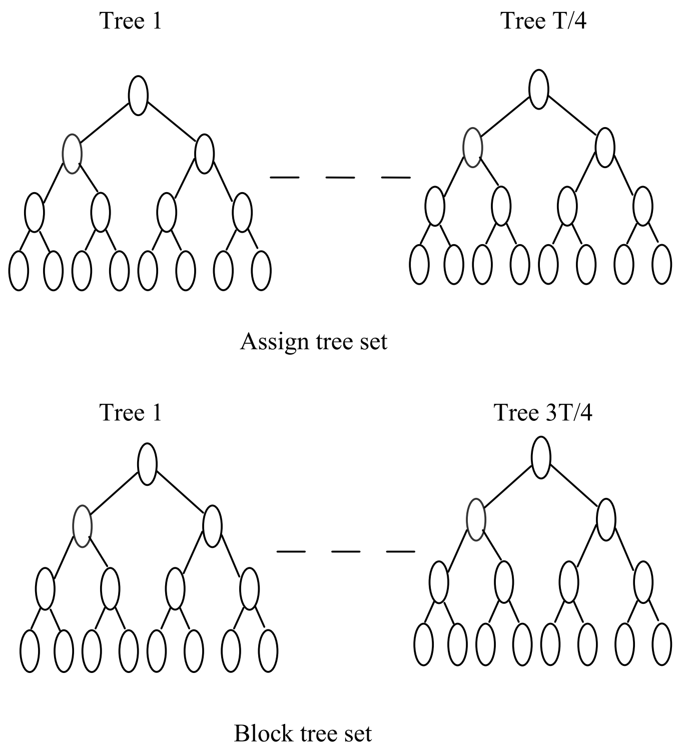


Figure 3.11 Division of trees into assign tree set and block tree set

the value of T_A and T_B depends upon the number of layers in the system. The total number of trees in block tree set is $T_B = (L_1 - 1)T / L_1$. In the proposed assignment scheme, there are three possible statuses of the codes as explained below,

Busy code: User occupied code in the *assign tree set* orthogonal to all the codes in the *assign tree set.*

Blocked code: Code blocked in the *block tree set* not orthogonal to the busy code.

Vacant code: Unoccupied code in the *assign tree set* orthogonal to the busy code.

The trees in the *Assign tree set* are used only for assignment and status is either vacant or busy. No ancestors and descendants of code in these trees are blocked because all the codes in these trees are orthogonal to each other. The scheme divides all the orthogonal and non orthogonal codes in separate groups. In previous OVSF assignment schemes, codes in the same layer only were orthogonal to each other. So, if we assign a code from

$\underline{Layer\ 1:}$

$$\begin{aligned}
&Let\ C_{l,n}\ is\ the\ assigned\ code\\
&let\ x\ =\ 2^{L\text{-}2\text{-}l}(n\text{-}1)+2\times T_A\times 2^{L-l}\\
&\underline{Ancestors\ blocked}\\
&\begin{cases} C_{l,\left(\left\lceil \frac{n}{2^{l\text{-}1}}\right\rceil\right)} & l=L\\ C_{l,\left(\left\lceil \frac{n}{2^{l\text{-}1}}\right\rceil+\left(2\times T_A\right)^{L\text{-}l}\right)} & l=2,3,\ldots L\text{-}1\end{cases}
\end{aligned}\tag{3.6}$$

$\underline{Layer\ 2:}$

$$\begin{aligned}
&Let\ C_{2,n}\ is\ the\ assigned\ code\\
&let\ x\ =\ 2^{L\text{-}2\text{-}l}(n\text{-}1)+2\times T_A\times 2^{L-l}\\
&\underline{Ancestors\ blocked}\\
&C_{l,\left(\left\lceil \frac{n}{2^{l\text{-}1}}\right\rceil+\left(2\times T_A\right)^{L\text{-}l}\right)}\quad l=3,4,\ldots L\\
&\underline{Descendants\ blocked}\\
&C_{1,x+1}\ and\ C_{1,x+2}
\end{aligned}\tag{3.7}$$

………………………………………..

$\underline{Layer\ L\text{-}1:}$

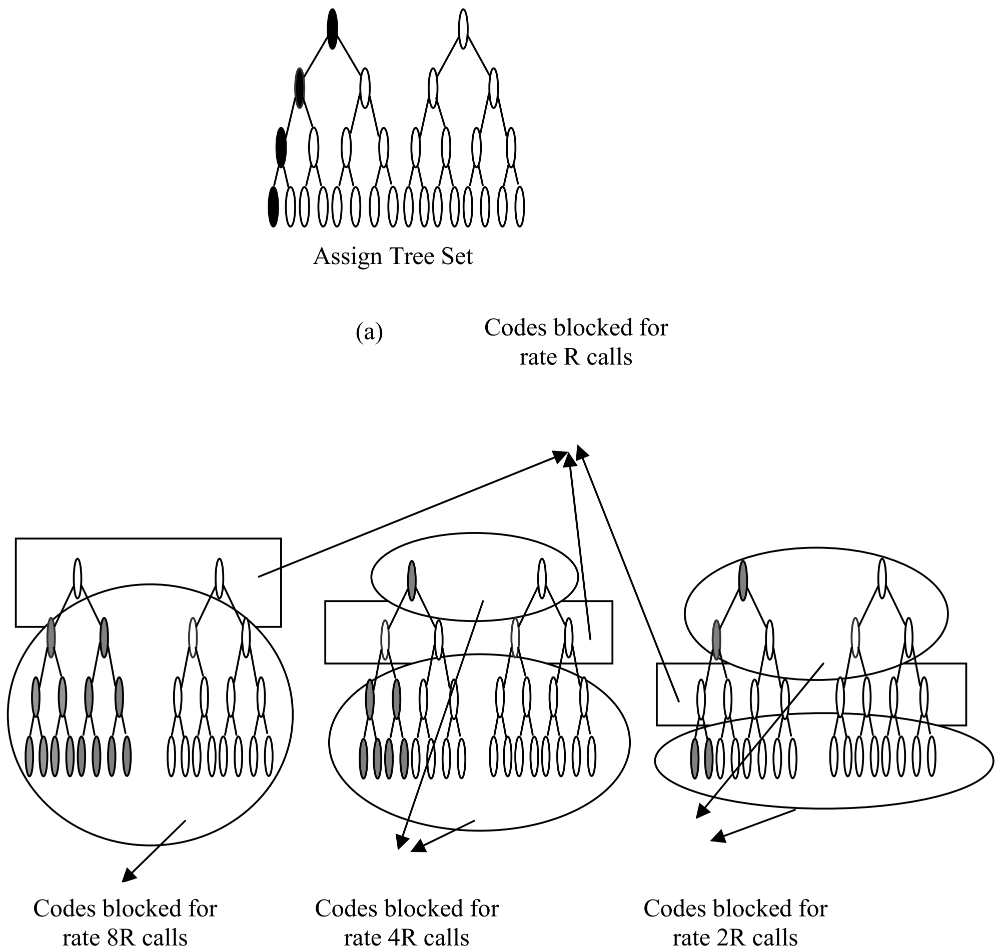
$$\begin{aligned}
&Let\ C_{L\text{-}1,n}\ is\ the\ assigned\ code\\
&let\ x\ =\ 2^{L\text{-}1\text{-}l}(n\text{-}1)+T_A\times 2^{L-l}\\
&\underline{Ancestors\ blocked}\\
&C_{L,\left(\left\lceil \frac{n}{2^{l\text{-}1}}\right\rceil+\left(2\times T_A\right)^{L\text{-}1}\right)}\\
&\underline{Descendants\ blocked}\\
&C_{1,x+1}\ ,\ldots.\ C_{1,x+2}{}^{L-l-1}\quad l=3,4,\ldots,L\text{-}2
\end{aligned}\tag{3.8}$$

$\underline{Layer\ L:}$

$$\begin{aligned}
&Let\ C_{L,n}\ is\ the\ assigned\ code\\
&let\ x\ =\ 2^{L\text{-}l}(n\text{-}1)\\
&\underline{Descendants\ blocked}\\
&C_{1,x+1}\ ,\ldots.\ C_{1,x+2}{}^{L-l}\quad l=2,3,4,\ldots,L\text{-}1
\end{aligned}\tag{3.9}$$

Figure 3.12 Assignment and blocking in the FA scheme

the tree, its ancestor and descendant codes were blocked. Assume $C_{l,n}$ represents code in assign tree with code number n in the layer l with spreading factor 2^{L-l}. If code $C_{l,n}$ is assigned to user, the codes blocked in the block tree for layer 1,2,....,L_1-1,L_1 is shown in Figure 3.12. In Figure 3.12, L_1 is taken equal to L. The assignment and blocking of codes is further shown in Figure 3.13 for tree set (2, 6). The assignment of codes is shown in Figure 3.13(a) and the blocking is shown in Figure 3.13(b). Here we consider codes for



Block Tree Set

(b)

Figure 3.13 (a) Assignment of codes in FA scheme
(b) Blocking of codes in FA scheme

four data rates R, $2R$, $4R$ and $8R$. The maximum capacity of the system considered is 8×8=64R. The blocked codes are represented with circles as shown in Figure 3.13(b), corresponding to 8*R,* 4*R* and 2*R* calls. The blocked codes are for rate *R* calls are represented by rectangles. Using the proposed scheme, the searching process consumes significantly less time because small proportion (25% in the example shown) of codes are to be searched. One of the possible limitations of the proposed scheme is increase in the code blocking when the arrival distribution varies rapidly. The code blocking in FA scheme can be reduced by using reassignments as will be discussed in FRA scheme.

3.5.2 Flowchart and algorithm

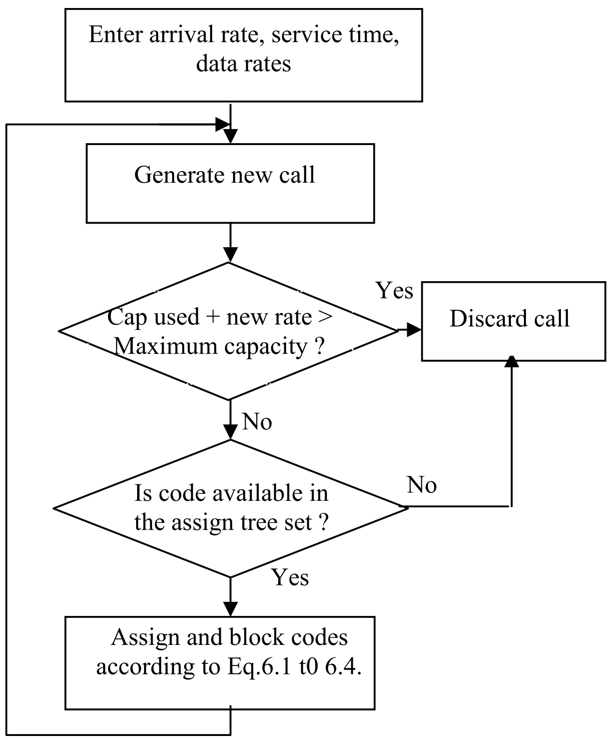


Figure 3.14 Flow chart of FA scheme

The flowchart of fast assignment scheme is given in Figure 3.14. The algorithm is outlined below

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. Generate new call. For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.

3. If the rate of new call is more than the available capacity of the code tree, call is discarded. If the new call is within the code tree capacity, the availability of vacant code is checked in the assign tree set.

4. If code is available, the code assignment and blocking is done according to Equations 3.6-3.9.

5. If vacant code is not available call is discarded.

3.6 Fast Reassignment (FRA) scheme

3.6.1 Description

In fast reassignment scheme, the trees are denoted by group (T_A, T_S, T_B), where T_A, T_B are defined as earlier and T_S is the *spare tree set.* The codes in the *spare tree set* are not orthogonal to its ancestors and descendants like previous scheme OVSF codes and unlike *assign tree set.* When a new call arrives, availability of the vacant codes is checked in the assign tree set. If code is available it is assigned according to FA scheme. If code is not available in the assigned tree set, vacant code is searched in the spare tree set. If the code is available, it is assigned to the incoming call and all of its ancestors and descendants are blocked. In FRA scheme, a threshold for the number of codes is set for different rates (layers). When the number of assigned codes reached a threshold, a new call is passed to the spare tree set for checking the availability of vacant code. T_A and T_B are related to each other as in FA scheme. The number of trees in the *spare tree set* may be fixed or variable.

Higher the number of trees in the *spare tree set*, higher is the reduction in call blocking in the OVSF-CDMA system but the decision time may increases with the increase in the number of trees in the spare tree set. The FRA scheme is explained in Figure 3.15. Suppose we have tree set (2,2,6) with the total capacity of 80 units as shown in Figure 3.15(a), assume that the statuses of tree set are as shown in Figure 3.15(b) before the arrival of rate 4R call. There is no vacant code available in the assign tree set as the threshold of 4R is exceeded, but the vacant code is available in the spare tree set. The vacant code from the left is assigned to the call. All the ancestors and descendants of the codes are blocked according to Table

3.6.2 Flowchart and algorithm

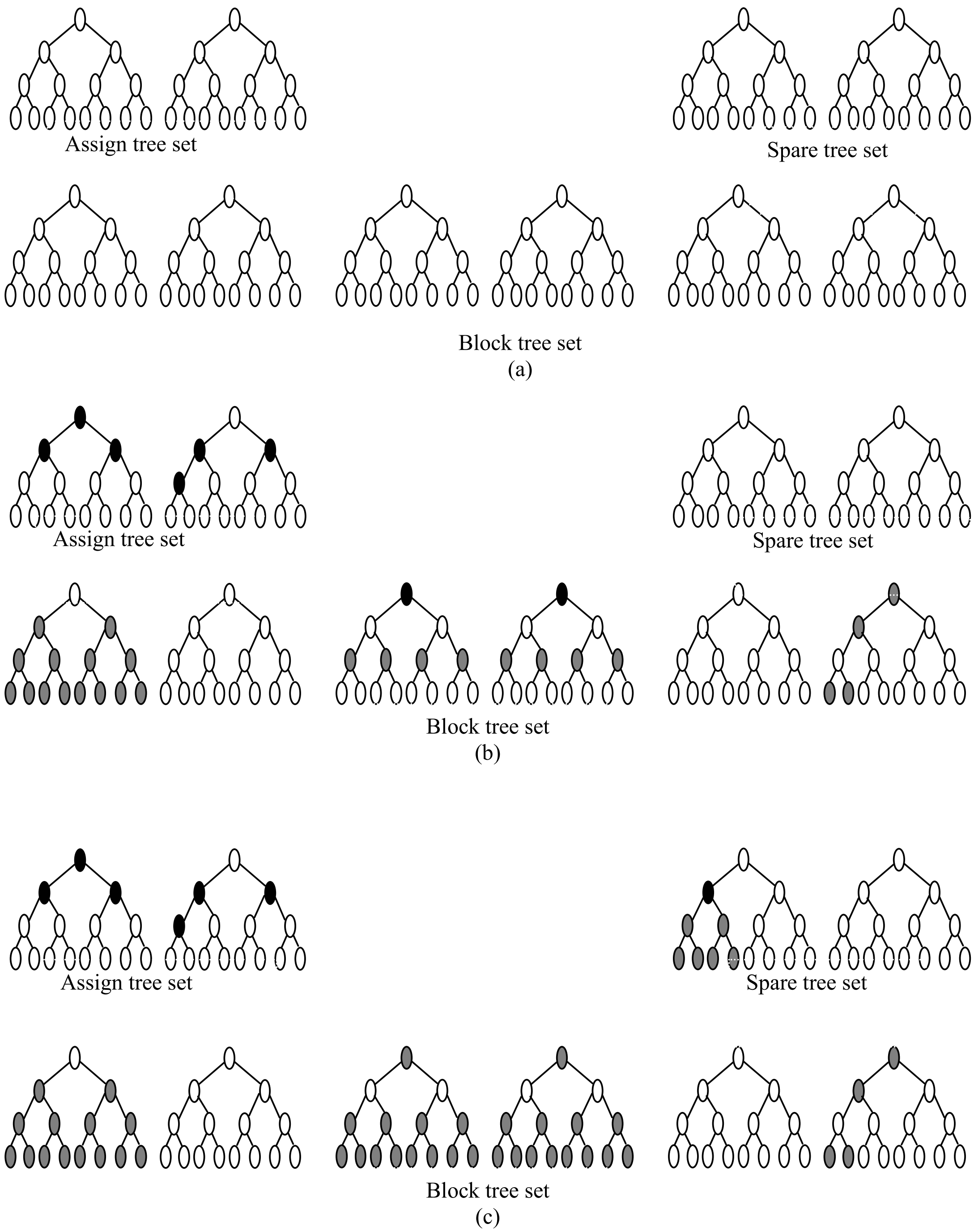


Figure 3.15 Illustration of FRA scheme
(a) Division of trees in (2,2,6) sets
(b) Status of trees before arrival of 4R call
(c) Status of trees after handling 4R call

The flowchart of fast assignment scheme is given in Figure 3.16. The algorithm is outlined below

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. Generate new call. For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.

3. If the rate of new call is more than the available capacity of the code tree, call is discarded. If the new call is within the code tree capacity, the availability of vacant code is checked in the assign tree set.

4. If code is available, the code assignment and blocking is done according to Equations 3.6-3.9.

5. If vacant code is not available, the vacant code availability is checked in the spare tree set. If code is available, it is given to the incoming call. If vacant code is not available, the call is discarded.

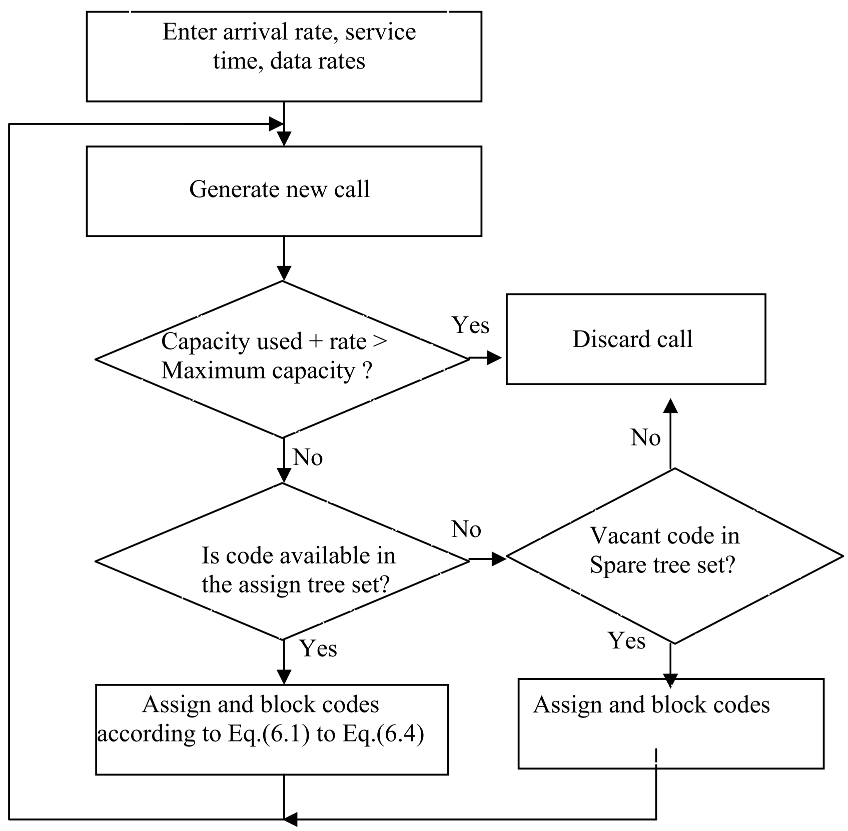


Figure 3.16 Flow chart of FRA scheme

3.6.3 Performance analysis

We consider four different arrival classes $\lambda \in \{\lambda_0, \lambda_1, \lambda_2, \lambda_3\}$. The total number of codes in the system is, $G_0 + G_1 + G_2 + G_3$, where G_X is the total number of codes corresponding to class x in the system. The service time is 1/μ for all traffic classes. In this section we derive the expression for number of codes checked for proposed assignment and reassignment scheme along with LCA and DCA scheme. The total number of codes checked (N) before suitable vacant code can be calculated for different schemes as follows

LCA/RA

$$N = T \times 2^{L-l} \tag{3.10}$$

DCA

When reassignments not required

$$N = T \times 2^{L-l} \tag{3.11}$$

When reassignments required

$$N = T\left(2^{L-l} + 2^{L-l+1} + ...+ 2^{L-1}\right) \tag{3.12}$$

FA

$$N = T_A \times 2^{L-l} \tag{3.13}$$

FRA

$$N = T_A \times 2^{L-l} + T_S\left(2^{L-l} + 2^{L-l+1} + ...+ 2^{L-1}\right) \tag{3.14}$$

From Equation 3.10-3.14 we see that codes searched are least for *FA* scheme. In *FRA* scheme the number of codes checked increases to compensate reduction in code blocking.

The blocking probability for the code group $k \in \{0,1,2,3\}$ is given as

$$P_K = \frac{\rho_k^{G_k} / G_k!}{\sum_{n=1}^{G_k} \rho_k / n!} \tag{3.15}$$

In Equation 3.15 $\rho_k = \lambda_k / \mu$ is the traffic load for class k calls.

3.6.4 Input Parameters

- Call arrival process is Poisson with mean arrival rate, λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value, *1/μ* =1 units of time.

- Possible *OVSF* code rates are *R,* 2*R,* 4*R* and 8*R*.
- Tree set considered is (4,12) for FA scheme and (3,4,9) for FRA scheme. The sets are chosen to make the maximum capacity equal to 128R.

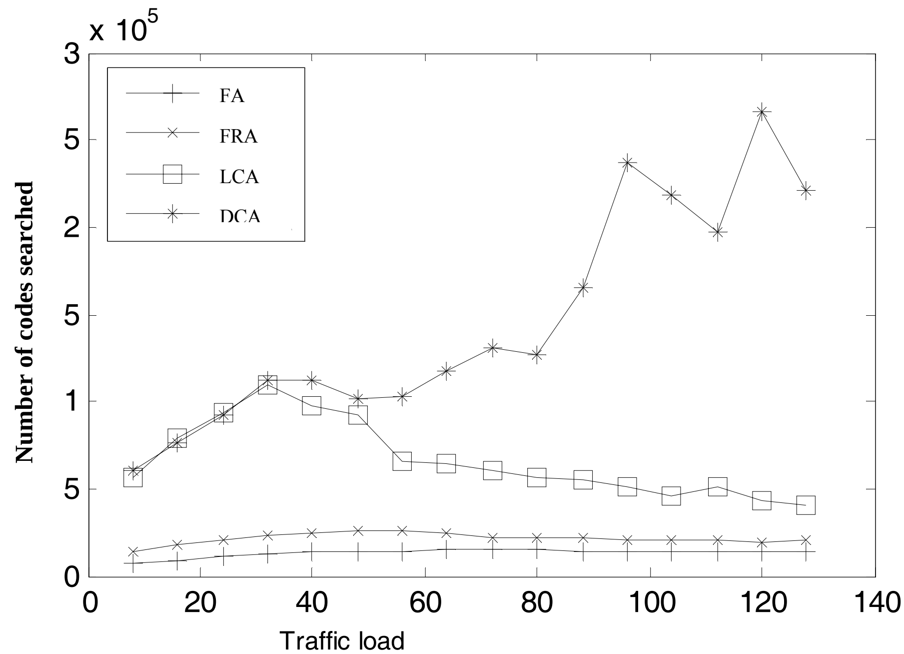


Figure 3.17 Number of codes checked for distribution [0.25,0.25,0.25,0.25]

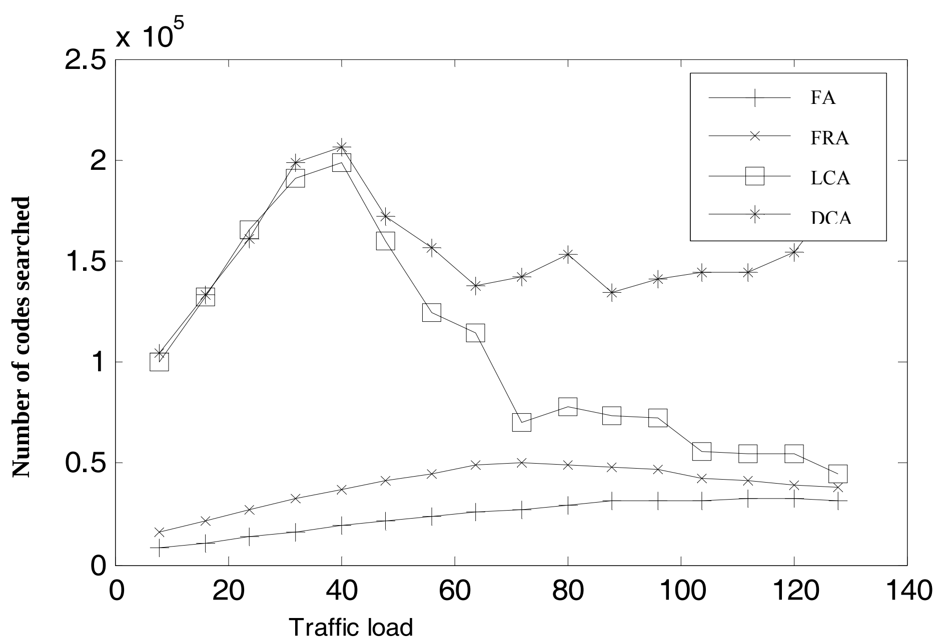


Figure 3.18 Number of codes checked for distribution [0.4,0.4,0.1,0.1]

3.6.5 Results

We compare the performance of FA and FRA scheme with LCA and DCA schemes. The simulation is done for 5000 users and result is average of 10 simulations. The number of

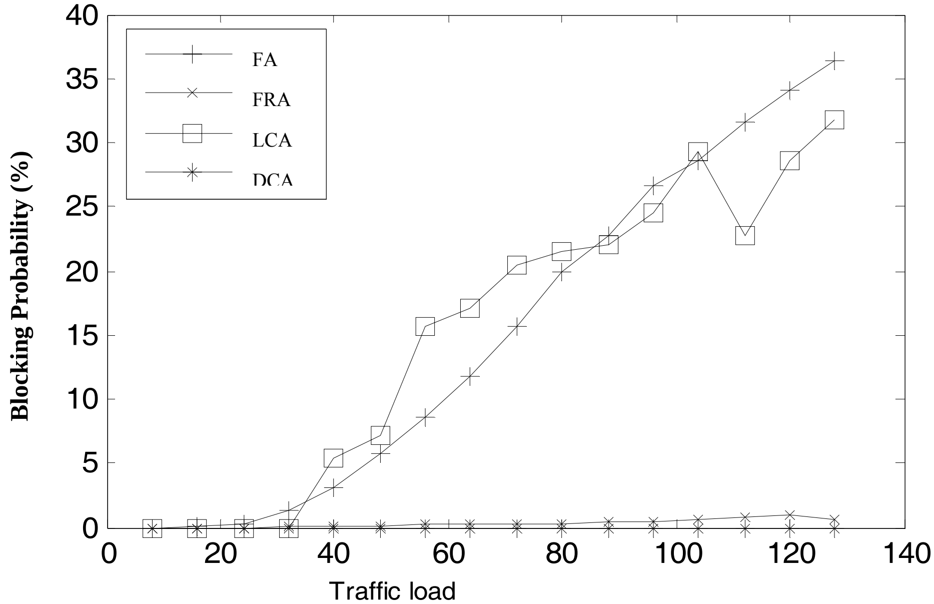


Figure 3.19 Blocking Probability vs traffic load for distribution [0.25,0.25,0.25,0.25]

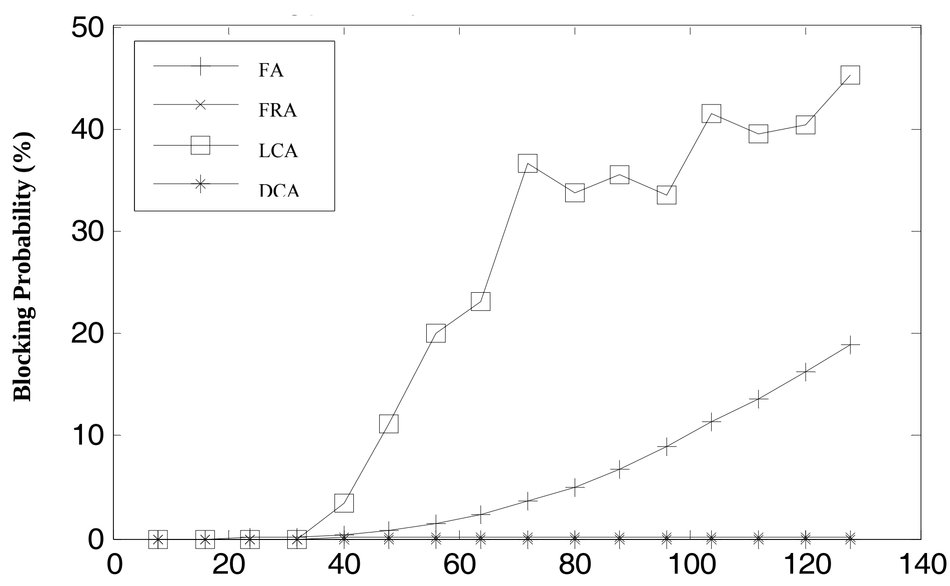


Figure 3.20 Blocking Probability vs traffic load for distribution [0.4,0.4,0.1,0.1]

codes checked for each scheme is plotted in Figure 3.17 and Figure 3.18. Results show that FA and FRA schemes need significantly small number of codes compared to LCA and DCA schemes. The blocking probability performance (Figure 3.19-3.20) in FA scheme can be inferior to both LCA and DCA schemes which can be improved using FRA scheme. We consider probabilities for different class users as (p_1, p_2, p_3, p_4), where p_1, p_2, p_3 and p_4 are the probabilities of arrival rate R, $2R$, $4R$ and $8R$ users.

3.7 Summary

In this chapter we propose a number of fast code assignment schemes to reduce the decision time for appropriate vacant code. The RBA scheme uses code reservation according to the probability density function of input traffic classes. So the number of codes checked before suitable codes are a function of number of groups (classes) considered. The blocking probability may increase if the distribution of arrival rates deviates from uniform. To reduce the blocking probability in RBA scheme, reassignments may be applied as considered in the RBR scheme. Therefore RBA and RBA schemes can be chosen according to arrival class distributions. The adaptive tree properties schemes uses the properties of trees like number of used trees, number of vacant codes and available capacity to reduce the code blocking in RBA schemes further.

FA scheme divide the tree into two parts named assign tree set and block tree set. The codes in the assign tree set are only used for assignment and are orthogonal to each other irrespective of the layer number. The number of codes searched reduces exponentially as we go down the tree. This decreases decision time rapidly as we go to layer 1 from layer 8. This scheme works well under uniform load conditions. For non-uniform load conditions, FRA scheme can be used to reduce the blocking problem in the FA scheme. In FRA scheme, the code tree is divided into three sets namely assign tree set, block tree set and reassign tree set. The definition of assign tree set and block tree set is same as FA scheme and reassign tree set is used to handle load under non-uniform rates distribution.

CHAPTER 4

Code assignment using multiple rake combiners

4.1 Introduction

Single code assignment schemes cannot guarantee very small blocking probability. The multi-code assignment schemes can reduce code blocking to a very small value

Table 4.1 Meanings of different notation used

Notation	Definition
L	Number of layers in WCDMA downlink OVSF code tree
$C_{l,n}$	Code in layer l with branch number n
NC_x	Number of codes with spreading factor x.
NR_x	Number of rakes required corresponding to SF x.
W_C	Wastage capacity for a multi-code
VC_{2^x}	Number of vacant codes corresponding to spreading factor 2^x
BC_{2^x}	Number of busy codes corresponding to spreading factor 2^x
SF_x	Spreading Factor x
MSF	$MSF = [VC_{SF_{2^n}}, VC_{SF_{2^{n-1}}}, VC_{SF_{2^{n-2}}}, \ldots .VC_{SF_{2^0}}]$, Multi-spreading factor giving the number of vacant codes available with the SF $2^n, 2^{n-1}, 2^{n-2}, \ldots .2^0$.
a_{2^x}	Code coefficients corresponding to SF_x with possible values $2^0, 2^1, \ldots, 2^{7-x}$. a_{2^x} varies form 0 to 2^{n-x}, where the request rate is $2^n R$
$Req(k_1,k_2)$	Request for rate k_1 by user with k_2 rake combiners
$\bar{l} = [l_1, l_2, \ldots . l_m]$	Array for m non-zero coefficients, l_x is the position of x_{th} non-zero coefficient
MC	$MC = [a_{2^0}, a_{2^1}, a_{2^2}, \ldots ., a_{2^7}]$

depending upon the number of codes used for incoming calls. More is the number of codes used, lesser is the OVSF code blocking. The use of more codes for one call requires the use of multiple rake combiners at the BS and at the UE as compared to single rake combiners for single code assignment schemes. The code tree fragmentation can also be minimized using multiple codes for the same call. Also, the code rate wastage (to be defined later) reduces as the number of rake combiners is increased.

4.2 Multi-code assignment scheme

The different symbols and notations used in the multi-code approach are listed in Table 4.1. We define multicode $MC = [a_{2^0}, a_{2^1}, a_{2^2}, ..., a_{2^7}]$, where a_{2^x} is the number of codes corresponds to spreading factor 2^x used to handle new call. Consider a new call with the requirement of rate 2^nR. We describe an algorithm for finding optimal arrangement of codes and number of rake combiners for new call. We first explain the procedure for quantized data rates in the form of 2^nR. Then we explain the procedure for non-quantized data rates, where we treat non-quantized data rates as sum of quantized data rates. So, the procedure to handle non quantized call becomes similar to call handling for quantized rate calls.

4.3 Quantized Data Rate

The procedure for finding optimal number of rakes and codes for quantized data rate in the form of 2^nR is divided into three steps

1. Find the different terms which satisfy the capacity requirement given by

$$2^0 a_{2^0} + 2^1 a_{2^1} + 2^2 a_{2^2} + \ldots\ldots + 2^{n-1} a_{2^{n-1}} + 2^n a_{2^n} = 2^n \quad (4.1)$$

2. Total number of possible terms is divided into two categories
    a. Terms producing unique combinations
    b. Terms producing multiple combinations
3. Find the optimal combination of codes and multiple rake combiners for the result obtained in step 2.

4.3.1 Finding total combinations for rate $2^n R$

Consider left side of Equation 4.1. For a new call with rate 2^nR to satisfy the capacity requirement, the number of possible combinations for coefficients $a_{2_0}, ... a_{2^n}$ is 2^n. Table 4.2 gives the total number of possible terms with 0 to n non-zero coefficients. It also

Table 4.2 Terms satisfying capacity constraint

Number of non zero coefficients (r)	Number of terms (p)	Term Validity Condition
0	1	Not allowed
1	n	$2^{x} a_{2^{x}} \leq 2^{n}; x \in \{0,1,....n\}$
2	$\frac{n!}{2!(n-2)!}$	$2^{x1} a_{2^{x1}} + 2^{x2} a_{2^{x2}} \leq 2^{n}; x1, x2 \in \{0,1,....n\}$
3	$\frac{n!}{3!(n-3)!}$	$2^{x1} a_{2^{x1}} + 2^{x2} a_{2^{x2}} + 2^{x3} a_{2^{x3}} \leq 2^{n}; x1, x2, x3 \in \{0,1,....n\}$
….	….	….
m	$\frac{n!}{m!(n-m)}$	$2^{x1} a_{2^{x1}} + 2^{x2} a_{2^{x2}} + ... + 2^{xm} a_{2^{xm}} \leq 2^{n}; x1, x2, ...xm \in \{0,1,....n\}$
….	….	….
n-2	$\frac{n!}{(n-2)!2!}$	$2^{x1} a_{2^{x1}} + 2^{x2} a_{2^{x2}} + ... + 2^{x(n-2)} a_{2^{xm}} \leq 2^{n}; x1, x2, ...x(n-2) \in \{0,1,....n\}$
n-1	n	$2^{x1} a_{2^{x1}} + 2^{x2} a_{2^{x2}} + ... + 2^{x(n-1)} a_{2^{xm}} \leq 2^{n}; x1, x2, ...x(n-1) \in \{0,1,....n\}$
n	1	Not allowed

gives the term validity condition for satisfying the capacity criterion given by Equation 4.1. Each of the coefficients $a_{2^{x}}, x \in [0,7]$ varies from 1 to 2^{n-x}.

4.3.2 Finding unique and multiple combinations

The possible terms with capacity constraint on the right hand side of Equation 4.1, are given in Table.4.3. All other terms are ignored. We divide number of terms (p) into two categories. In the first category, each term has single possible combination which satisfies the capacity constraint. The condition of uniqueness is given in Table 4.3. All

Table 4.3 Condition of uniqueness of a term

Non zero coefficients (r)	Condition of uniqueness of term
0	Not allowed
1	All are unique
2	$a_{2^{n-1}} = 2^{n-1}$
3	$a_{2^{n-1}} = 2^{n-1}, a_{2^{n-2}} = 2^{n-2}$
….	….
m	$a_{2^{n-1}} = 2^{n-1}, a_{2^{n-2}} = 2^{n-2}, \ldots., a_{2^{n-m+1}} = 2^{n-m-1}$
….	
n-2	$a_{2^{n-1}} = 2^{n-1}, a_{2^{n-2}} = 2^{n-2}, \ldots., a_{2^{1}} = 2^{3}$
n-1	$a_{2^{n-1}} = 2^{n-1}, a_{2^{n-2}} = 2^{n-2}, \ldots., a_{2^{0}} = 2^{2}$
n	Not allowed

the combinations which do not satisfy the uniqueness property fall in second category in which each term may have multiple combinations. For each of the term in second category, the algorithm for finding number of possible combinations is given as follows. Let the rate requirement is 2^nR. Let us consider that there are m non-zero coefficients in the term represented by array $\bar{l} = [l_1, l_2, \ldots. l_m]$, where $m \in [2, \ldots. n\text{-}1]$ and $l_1, l_2, \ldots. l_m$ is the position of 1^{st}, 2^{nd}, …, m^{th} non-zero coefficient.

1. Initiate a tree structure with m number of levels and root at level m. The root of the tree is represented by n zeros $[0,0,\ldots.0]$.
2. The number of non-zero coefficients in layer x, where $x \in [1,2,3,\ldots. m-1]$ is x-l at position $l_m, l_{m-1}, \ldots. l_{m-x+2}$. The number of non-zero coefficients in layer m is m at positions $l_m, l_{m-1}, \ldots. l_2, l_1$.

3. The first layer has one branch. Number of branches in the second layer is 2^{n-m+1}-1 which is equal to the maximum number of occupied codes. The remaining capacities using codes 1, 2, …. , 2^{n-m+1}-1(branch number 1,2,…. 2^{n-m+1}-1 in layer 2) is $2^n - 2^{l_{m-1}} \times 1, 2^n - 2^{l_{m-1}} \times 2, ... 2^n - 2^{l_{m-1}} \times (2^{n-m+1} - 1)$. The remaining capacity is to be used by codes at position l_1, l_2, …., l_{m-1}. Consider that the remaining capacity in layer 2 and first branch is represented by R_c. For R_c, the number of branches in the third layer is $[(R_c / l_{m-1}) - 1]$. Similarly we can calculate the number of branches in layer 3 for second and third branch in layer 2. The total number of branches in layer 3 is addition of all the branches emerging from 3 branches of layer 2. The procedure is repeated till layer *m*.
4. The total number of combinations for the term is equal to the number of leaves.
5. The number of rake combiners is the addition of all the non-zero coefficient values for each array at the leaves of tree.

As an example, consider the arrival of call request with data rate 32*R*. The Equation 4.1 becomes $2^0 a_{2^0} + 2^1 a_{2^1} + 2^2 a_{2^2} + 2^3 a_{2^3} + 2^4 a_{2^4} + 2^5 a_{2^5} = 32$. There are six coefficients

Table 4.4 Example illustrating number of unique and multiple terms

No. of non-zero coefficients	Total terms	Valid terms	Terms with unique combination	Terms with multiple combinations
0	0	0	0	0
1	6	5	5	0
2	15	10	4	6
3	20	10	3	7
4	15	5	2	3
5	6	1	1	0
6	1	0	0	0

and for the rate constraint, the number of non-zero coefficients varies from 1 to 5 ($a_{2^0}, a_{2^1}, ... a_{2^4}$). The terms with different non-zero coefficients are put in tabular form shown in Table.4.4.

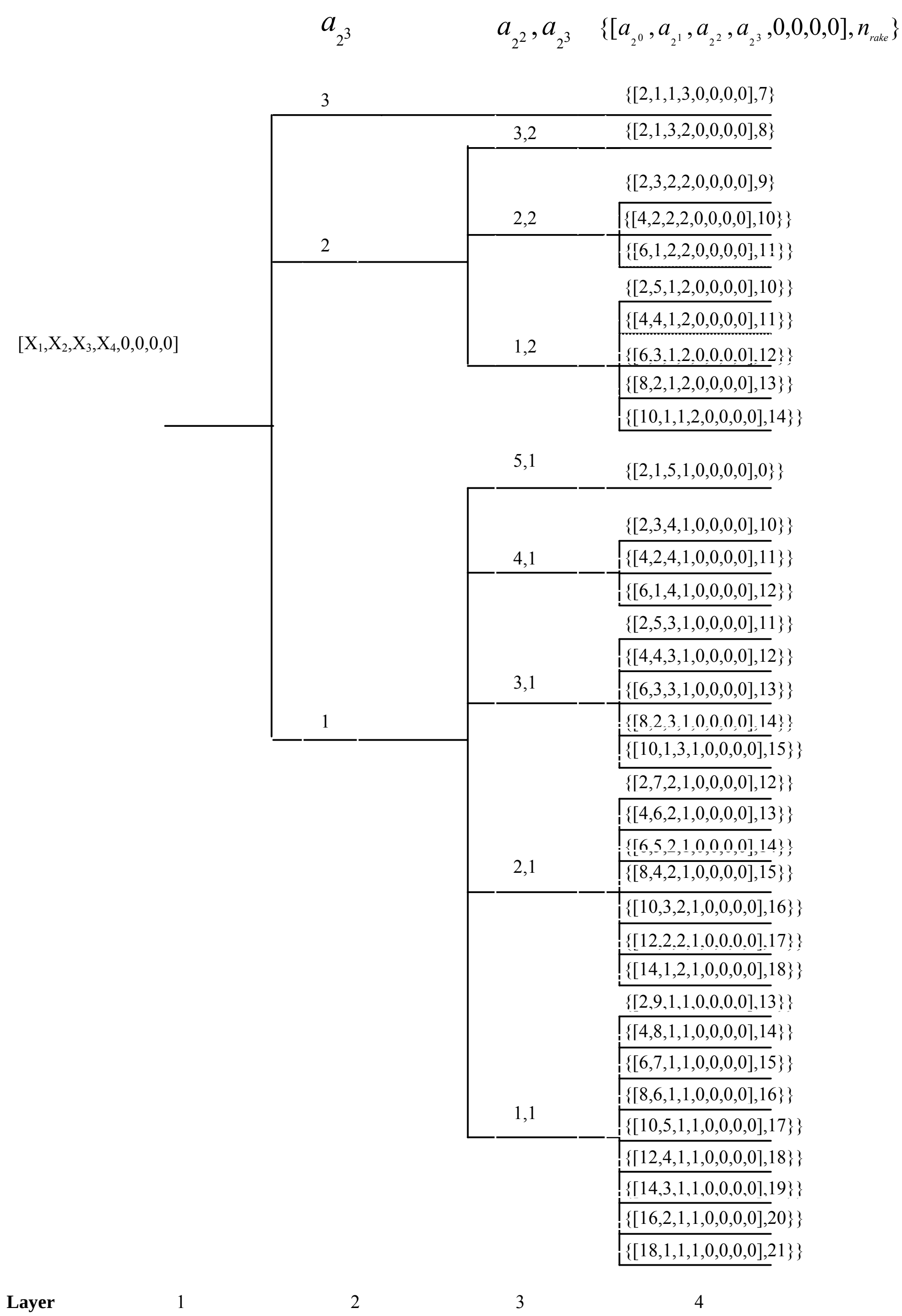


Figure 4.1 Procedure for finding code-rake combinations for term [X_1,X_2,X_3,X_4,0,0,0,0], where X_n represents non-zero term at location n. In term $\{[a_{2^0}, a_{2^1}, \ldots, a_{2^7},], n\}, a_{2^x}$,represents number of non-zero elements at location x-1, n is the number of rake combiners required for the combination

We consider a term with four non-zero coefficients. The procedure for finding all the

Table 4.5 Illustration of number of code fragments for multi-code selection

Multi-code	Cdes needed	MSF	Code fragments
[0,0,0,1,0,0,0,0]	1	[2,4,4,1,0,0,0,0]	11
[0,0,2,0,0,0,0,0]	2	[2,4,2,2,0,0,0,0]	10
[0,2,1,0,0,0,0,0]	3	[2,2,3,2,0,0,0,0]	9

combinations along with the number of rake combiners is $a_{2^0}, a_{2^1}, a_{2^2}$ and a_{2^3} shown in Figure 4.1. The combination can be picked according to the number of rake combinersequipped in the UE.

4.3.3 Finding optimal number of codes and rake combiners

Define $MSF = [VC_{SF_{2^n}}, VC_{SF_{2^{n-1}}}, VC_{SF_{2^{n-2}}}, ..., VC_{SF_{2^0}}]$ as the multi-spreading factor giving the number of vacant codes available with the SF 2^n, 2^{n-1}, 2^{n-2},…., 2^0. The maximum number of vacant codes with SF 2^x is $C_{SF_{2^x}} + 2 \times C_{SF_{2^{x-1}}} + 2^2 C_{SF_{2^{x-2}}} + ... + 2^x C_{SF_{2^0}}$. Initially when the code tree is completely vacant, $MSF = [0,0,0,0,0,0,0,4]$. For a new call with the requirement of $2^n R$ capacity and k rake combiners, the problem is to assign the set of codes to the request in such a way that the sum of the remaining elements in *MSF* is least. The number of rake combiners used may vary from 1,2,….*k*. In case more combinations produces same sum, the combination using lesser number of codes is preferred. To illustrate optimality criterion, consider that vacant codes in the code tree at any time is $MC = [2,4,4,2,0,0,0,0]$. Consider that the new user arrive with the requirement of rate 8R and equipped with three rake combiners. The different multi-code combinations possible are given in Table.4.5. The multi-code [0,2,1,0,0,0,0,0] provide least number of code fragments and will be the desired combination. Now consider that the status of vacant codes is [1,1,1,1,0,0,0,0]. Different multi-codes are shown in Table.4.6. The code fragments using any of the three combinations are same. The multi-code [0,0,0,1,0,0,0,0] uses least number of sub codes and will be used for new call.

4.4 Non-quantized Data Rate

Table 4.6 Multi-code selection for same number of code fragments

Multi-code	Codes needed	MSF	Code fragments
[0,0,0,1,0,0,0,0]	1	[1,1,1,0,0,0,0,0]	3
[0,0,2,0,0,0,0,0]	2	[1,1,1,0,0,0,0,0]	3
[0,2,1,0,0,0,0,0]	3	[1,1,1,0,0,0,0,0]	3

When the incoming call is kR is not quantized the, the number of rake combiners is calculated as

- Find the minimum m_0 such that $k \geq 2^{m_0} R$.
- Find $k_0 = k - 2^{m_0}$
- Find the minimum m_1 such that $k_0 \geq 2^{m_1}$
- Find $k_1 = k_0 - 2^{m_1}$
- ….
- Till k_x=2^m, $m \in [0,....7]$
- Find the number of codes and rake combiners required for rates k_0R, k_1R,….k_xR denoted by NC_0, NC_1, …., NC_x and NR_1, NR_2,…., NR_x. The total number of codes required are NC_0+NC_1+….NC_x and the total number of rake combiners required are NR_1+NR_2+…..NR_x.

4.5 Input Data

- Call arrival process is Poisson with mean arrival rate λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value $1/\mu$ =1 units of time.
- Possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes
- Total number of codes in layer 8 is 16.

4.6 Flowchart and algorithm

The flowchart of the simulation program is given in Figure 4.2. An outline of the simulation program is as follows.

1. Input parameters such as call arrival rate, duration, code rate distributions are entered.

2. For each new call, the capacity check is performed. If the call cannot be supported, the call is dropped.

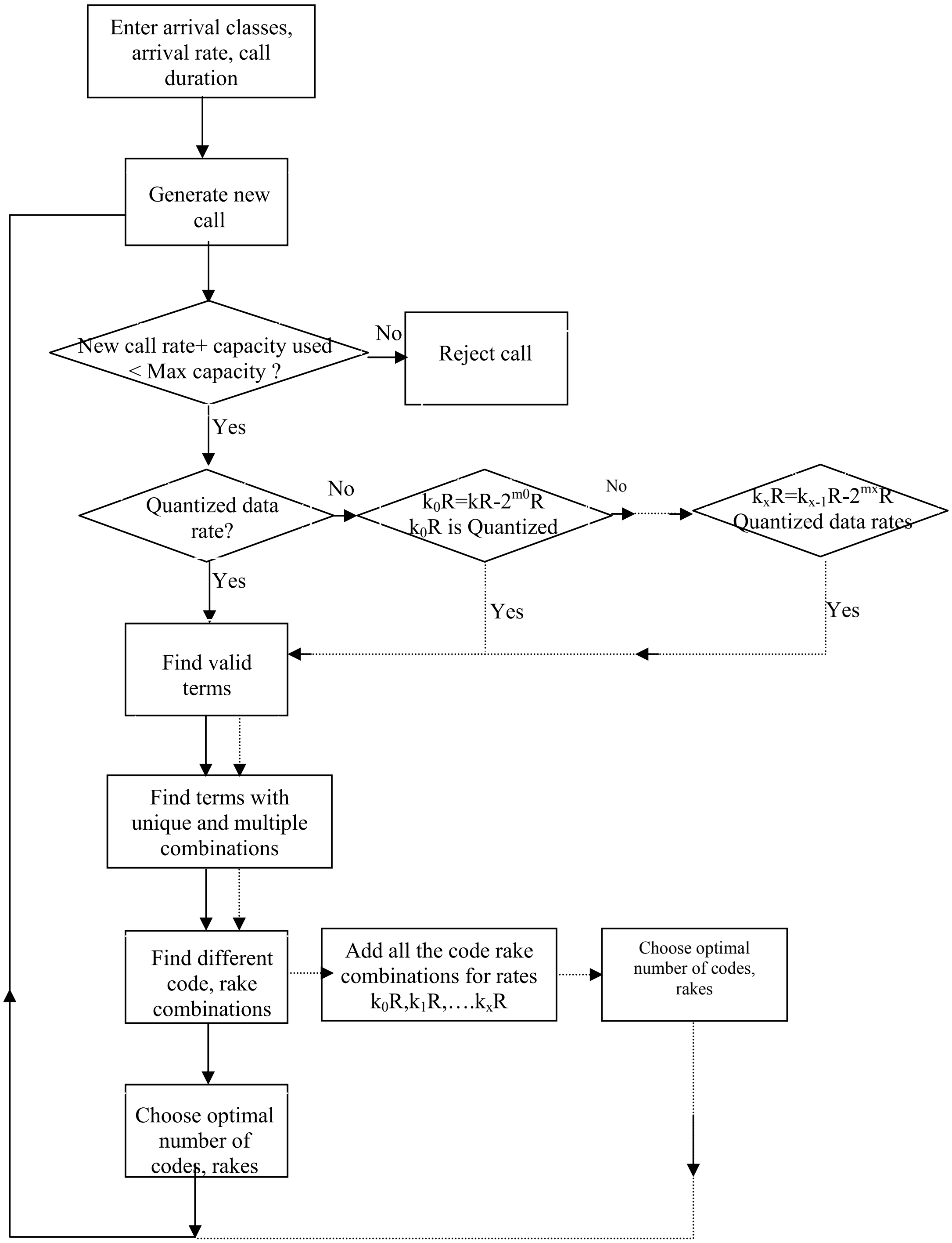


Figure 4.2 Flow chart of the MRC scheme

3. If the incoming rate is quantized, following steps are followed,
   - The total valid terms are calculated.

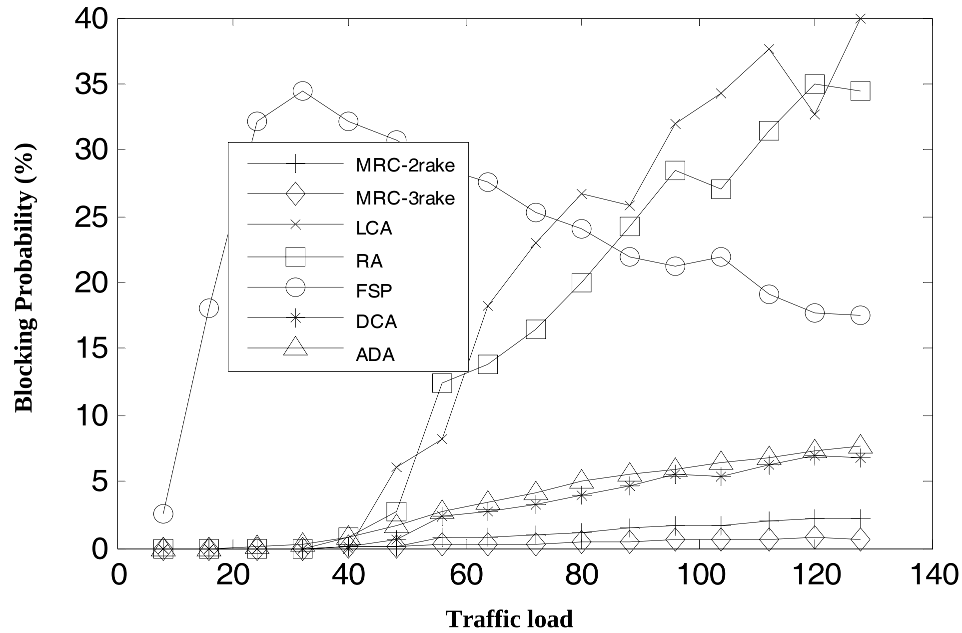


Figure 4.3 Blocking probability vs traffic load for uniform distribution

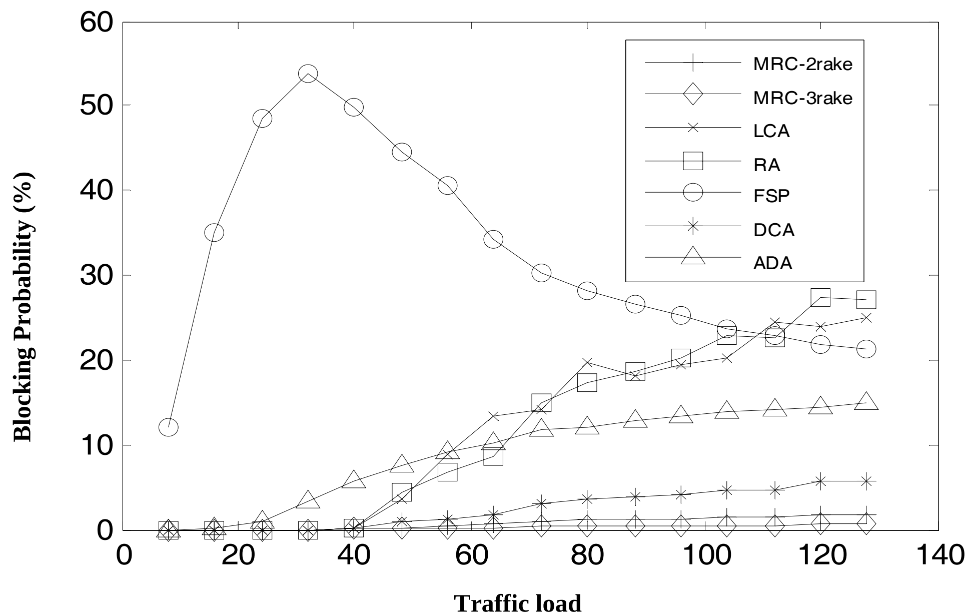


Figure 4.4 Blocking probability vs traffic load for more real time calls

- The valid terms are converted into terms with single combination and terms with multiple combinations.
- The different combinations are arranged for number of codes and number of rakes.

- Choose the optimal number of code-rake combination for the request.

4. If the input rate is not quantized, it is converted into set of quantized rated as described. Go to step 3.
5. The process is repeated by returning to Step 2.

4.7 Results

We compare the performance of MRC named MRC-2rake (using 2 rake combiners) and MRC-3rake (using 3 rake combiners) scheme with the performance of random assignment (RA), leftmost code assignment (LCA), fixed code assignment (FCP), adaptive code assignment (ADA) and dynamic code assignment (DCA) schemes discussed earlier. We consider probabilities for different class users as (p_1 ,p_2, p_3, p_4), where p_1, p_2, p_3 and p_4 are the probabilities of arrival rate R, $2R$, $4R$ and $8R$ users. We consider two different distributions of arrival classes. In the first case traffic load is uniform for the four arrival classes and in the second case, real time traffic rates dominates the traffic load. The simulation is done for 5000 users and result is the average of 10 simulations. Figure 4.3 and Figure 4.4 shows the performance improvement due to reduction in blocking probability.

4.8 Reducing code rate wastage using multiple rake combiners

4.8.1 OVSF code rate wastage

Consider a new user with rate kR searching for vacant code(s) in the OVSF code tree. Define a multi-code MC=[NC_8: NC_7: NC_6: NC_5: NC_4: NC_3: NC_2: NC_1], where NC_x is the number of codes in layer x used to handle rate kR. 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 of a multi-code is given by

$$W_c = \begin{cases} 0 & \mathrm{k} = \sum_{j=1}^{N} a_j 2^j \text{, where } a_x,\ \mathrm{x} \in [1, \mathrm{N}] \text{ takes values 0 or 1} \\ 0 & 0 < \mathrm{k} < N - 1 \\ W_{c'} & \text{where } W_{c'} \text{ depends on the number of rakes N and is given in Table 4.7.} \end{cases} \tag{4.2}$$

Table 4.7 OVSF code rate wastage variation with the number of rakes

Number of Rakes	Wastage Capacity ($W_{C'}$)
1	Assume k=k_1, $W_{C'} = \left\lceil \frac{2^{a_1} - k_1}{k_1} \right\rceil$; $2^{a_1 - 1} < k_1 < 2^{i}$
2	Assume $k_2 = k_1 - 2^{a_1 - 1}$ and $2^{a_2 - 1} < k_2 < 2^{a_2}$, where a_1, k_1 is defined as for 1-rake system $W_{C'} = \left\lceil \frac{2^{a_2} - k_2}{k_1} \right\rceil$
3.	Assume $k_2 = k_1 - 2^{a_1 - 1}, k_3 = k_2 - 2^{a_2 - 1}$ and $2^{a_3 - 1} < k_2 < 2^{a_3}$ where a_1, a_2, k_1 and k_2 are defined as for 1, 2 rake systems $W_{C'} = \left\lceil \frac{2^{a_3} - k_3}{k_1} \right\rceil$
……	…………………………………
8.	Assume $k_g = k_{g-1} - 2^{a_h - 1}$, where $g \in [1,8]$ and $a_h \in [a_1,a_8]$, where $a_1,a_2,\ldots,a_7$ and $k_1, k_2\ldots,k_7$ are defined as for rake 1,2,..,7 system $W_{C'} = \left\lceil \frac{2^{a_8} - k_8}{k_1} \right\rceil$

Using the formulae in Table 4.7, for an OVSF-CDMA system with *m* rake combiners and user rate less than 2^xR, where $x \in$ [0:7], the maximum code wastage capacity is (2^{x-m}-1)R and is shown in Table 4.8 for WCDMA system with 8 layer OVSF code tree.

4.8.2 Code sharing and reduction in wastage capacity

For *n*-rake system, consider a new call with rate k_0R, where $2^{i_0 - 1} < k_0 < 2^{i_0}$, the procedure starts dividing the rate into quantized and non-quantized parts. Assign vacant code with capacity $2^{i_0 - 1}R$ to the portion of the call. For $k_1 = k_0 - 2^{i_0 - 1}$, If k_1 is quantized, the vacant code with code capacity k_1R is assigned to the k_1R portion of k_0R. If k_1R is not quantized, find and $2^{i_1 - 1} < k_1 < 2^{i_1}$, find $k_2 = k_1 - 2^{i_1 - 1}$ 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

Table 4.8 Relation between data rate, wastage capacity and number of rake combiners in WCDMA downlink

Input Data rate	Maximum Wastage Capacity(WC_{max}) for 1 Rake	WC_{max} for 2-rake	WC_{max} for 3-rake	WC_{max} for 4-rake	WC_{max} for 5-rake	WC_{ax} for 6-rake	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

non-zero. For this case, code wastage takes place and the code wastage amount is $k_N - 2^{i_N - 1}$, where $2^{i_N - 1} < k_N < 2^{i_N}$. The portion k_NR of the rate k_0R is assigned to the vacant code and unused code capcity of the code is $\mathrm{WC}_1 = (2^{i_N} - k_N)R$. For the next non-quantized incoming calls find WC_2, WC_3,…, WC_M similar to WC_1. If the new call with the rate requirement of $k'R = \sum_{j=1}^{M} wc_j$ arrives, the code portions WC_1, WC_2,…, WC_{M} can be combined to handle new call. Therefore the code sharing allows the integration of vacant slots (code portions) to fulfill the request of new user. The slot management is the important part of the proposed code assignment scheme. In the following section, the code sharing is explained for single rake system. At any time t_0, the first call rate $i_0=k_0R$ arrives, where $k_0 \neq 2^n$, $n \in [0,7]$ and $2^{i-1}<k_0<2^i$. The wastage code capacity is $W_{C0}=(2^i-k_0)$. Consider the next non-quantized rate user $i_1=k_1$R, where $k_1 \neq 2^n$, $n \in [0,7]$ and $2^{j-1}<k_1<2^j$ seeking code. The wastage code capacity is equal to $W_{C1}=(2^j-K_1)$. If the next incoming rate is k_xR, where k_x may or may not be quantized, the wastage capacities are added such that $W_{C0}+W_{C1}+\ldots+W_{Cm}=k_xR$.

4.8.3 Reduction in code tree fragmentation

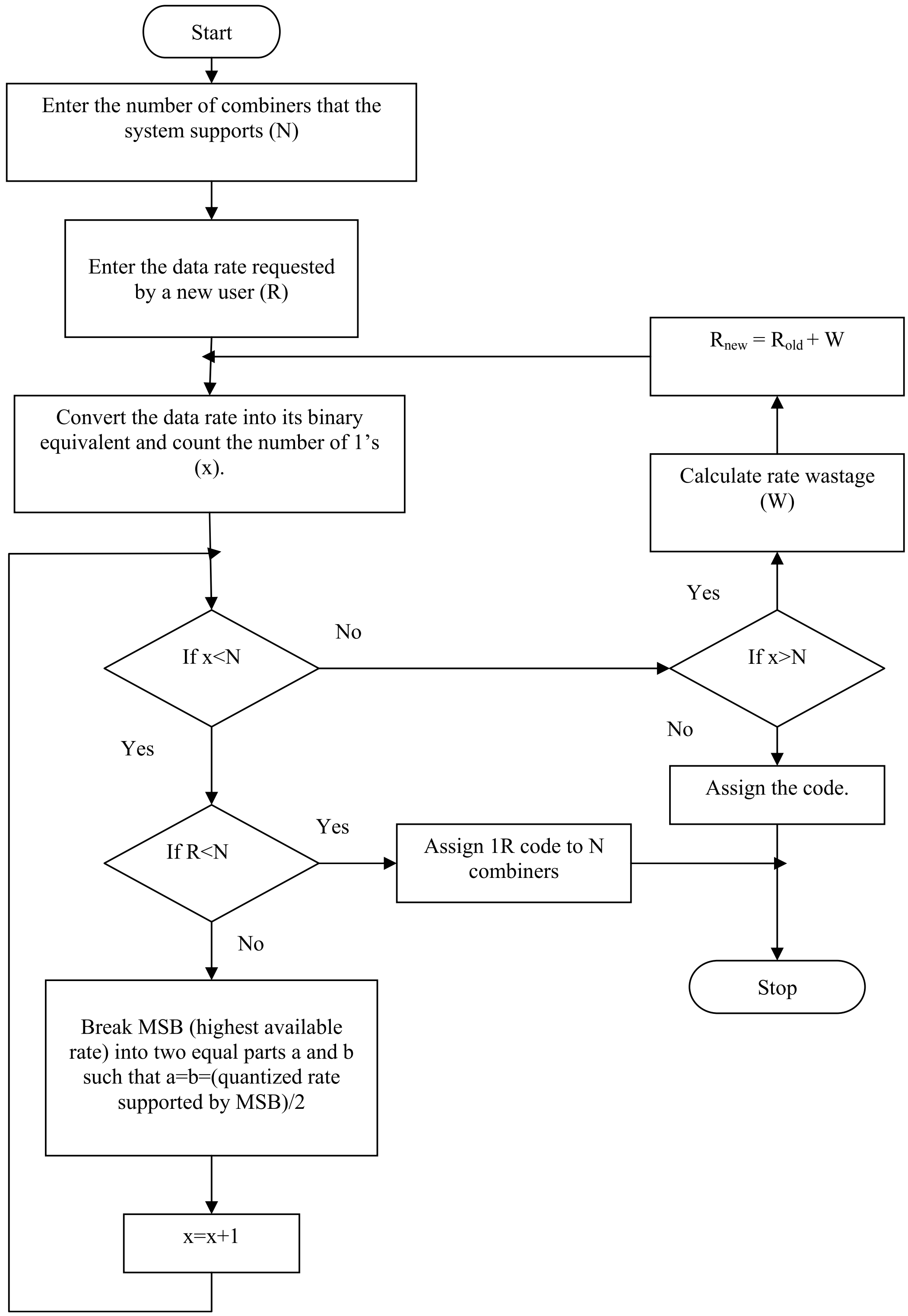


Figure 4.5 Flowchart showing reduction in code fragmentation

The aim of the section is to provide an algorithm for best use of multiple rakes for minimizing code tree fragmentation. According to definition higher is the number of less capacity codes are used to handle new call, lesser is the code tree fragmentation. The algorithm is shown in Figure 4.5. The aim is to convert bigger rates into smaller rates depending upon the number of rakes specified. The binary representation of the input arrival is used for conversion of higher rates into lower rates. This is possible due to binary nature of the code tree. The algorithm automatically breaks the rate into its quantized components.

We break Let the input rate is *x*R and there are *N* rake combiners in the system. The first step is to break the incoming rate into its quantized components. If there is an

Table 4.9 Relationship between number of combiners, rate wastage and code fragmentation

No of available combiners	Rate wastage (W)	Code fragmentation
1	9	32 R
2	1	16R, 8R
3	1	8R, 8R, 8R
4	0	16R, 4R, 2R,1R
5	0	8R, 8R, 4R, 2R, 1R
6	0	8R, 4R, 4R, 4R, 2R, 1R
7	0	4R, 4R, 4R, 4R, 4R, 2R, 1R

availability of another combiner we break the highest quantized component into two equal parts. If the unused combiners are still present, we again break the present highest data rate into two equal parts, this process continues till $x=N$, or in other words all combiners are made busy. Depending upon the number of rake combiners, rate wastage may be present in the system as in earlier discussion. As concluded earlier, if the number of quantized components is more than the number of rake combiners, there will be rate wastage. In our algorithm, we add wasted rate into the original rate to form a new rate and same procedure is repeated with the new data rate. Thus in any case we make smaller components for higher data rate. In case the rate is less than number of combiners, we assign 1R to R number of combiners. To illustrate the algorithm, consider a new user with data rate 23R. The binary equivalent is of 23 is 10111 and minimum

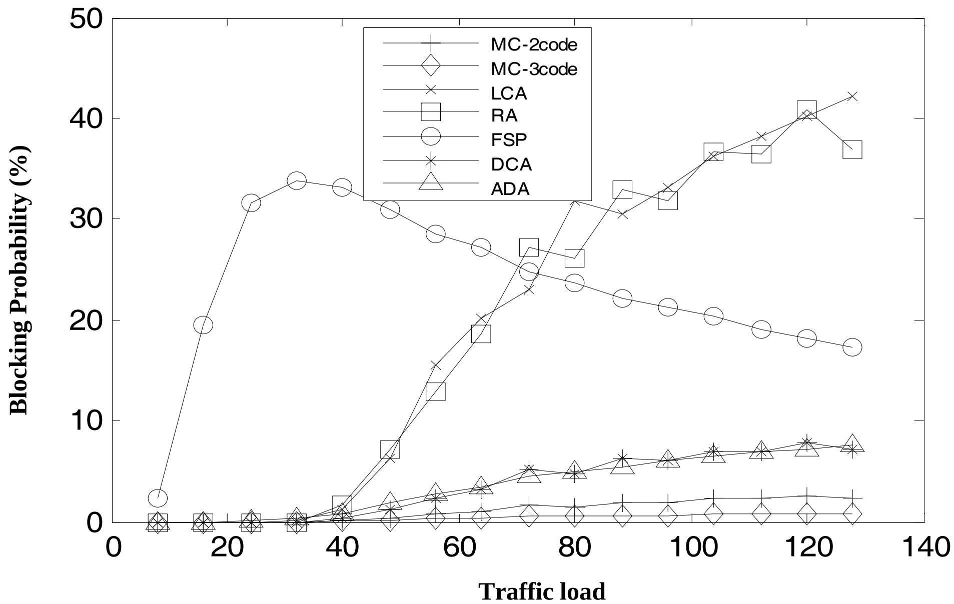


Figure 4.6 Blocking probability vs traffic load for uniform distribution

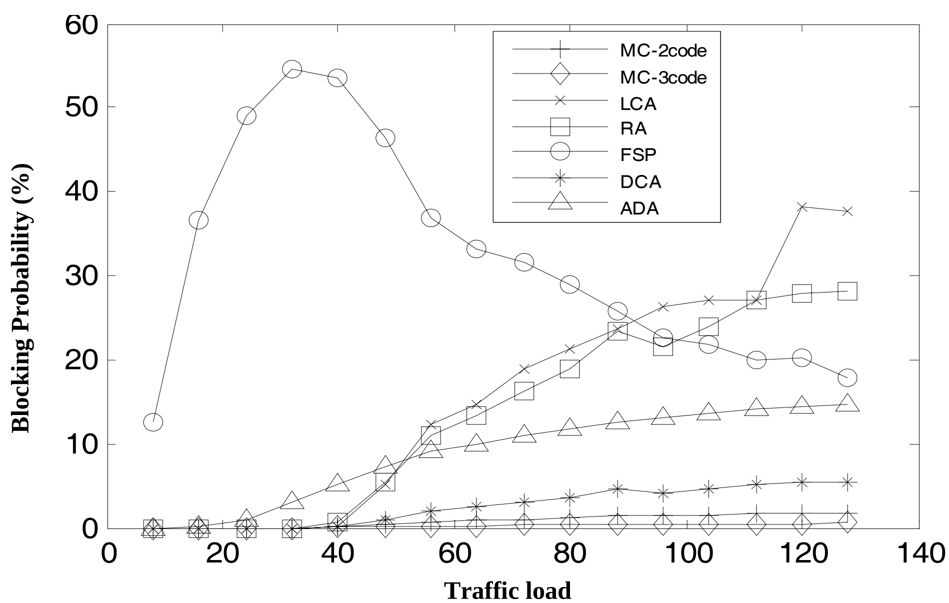


Figure 4.7 Blocking probability vs traffic load for dominating non-real time calls

number of combiners required is 4 to make code wastage zero. The relation between number of rake combiners, code rate wastage and efficient breaking using our algorithm is shown in Table 4.9. In this example we see that more the number of rake combiners, more is the rate fragmentation reducing the code tree fragmentation. This in turn leads to reduction in blocking probability keeping in mind that the possibility of availability of vacant higher layer codes increases.

4.9 Results

The input parameters used are

- Call arrival process is in accordance to Poisson with mean arrival rate, λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value, $1/\mu$ =1 units of time.
- Rates R-32R are assumed to be real time calls and rates 33R-128R are assumed to be non-real time calls.

In this section we compare the multi-code performance with provision of code fragmentation reduction and rate wastage reduction. We compare the proposed scheme

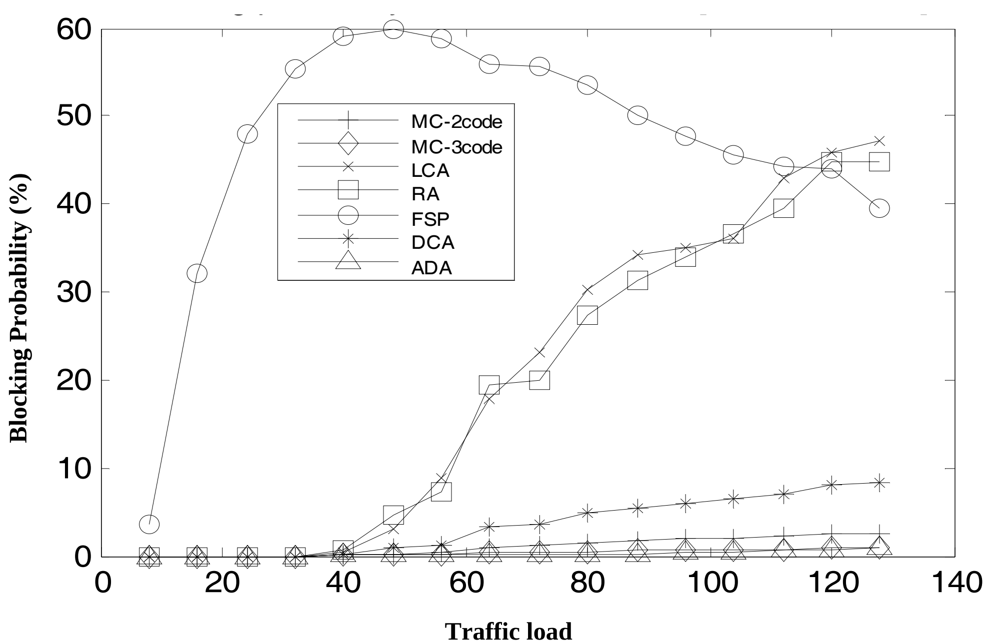


Figure 4.8 Blocking probability vs traffic load for dominating real time calls

named MC-2code (MC-3code) in which a new call be handled by combining the wastage capacity of two (three) codes with existing schemes LCA, RA, DCA, ADA and FSP schemes. The adaptive assignment scheme is RBA scheme discussed in chapter 3 and denotes adaptive code assignment scheme. In MC-2code and MC-3code schemes, we consider three distributions for the arrival rates. In the first case the probability of arrival of all rates is same. In the second case, the probability of non-real time calls is 75% and probability of real time calls is 25%. In the third case the probability of real time calls is 75% and probability of non-real time calls is 25%. The reduction in the code blocking in all the three cases is shown in Figure 4.6-4.8. The results show that the blocking probability using code sharing is least compared to earlier proposed schemes.

4.10 Summary

OVSF code tree has the property that the codes are able to handle the quantized rates only. For non-quantized calls single code assignment schemes are inefficient because of code rate wastage. The chapter described the multi-code assignment scheme. The benefits of the proposed scheme are less code blocking probability, less code tree fragmentation and getting optimal number of rake combiners. The non-quantized rates are recursively divided into quantized rate calls and multi-code can be used to handle the call. The multi-code use requires more rake combiners at the UE and BS increasing the complexity of WCDMA transceiver.

Appendix 4A

The algorithm is explained for finding the optimal number of codes and rake combiners for call arrival with the rate 20*R*. Find the largest integer m_0 such that $20 \geq 2^{m_0}$, which gives the m_0=4. $k_0=20-2^4=4$. As k_0 =4 is quantized, procedure of finding quantization rates is stopped. So finding optimal code-rake combination for 20R rate is equivalent to finding code-rake combinations for 16R and 4R differently and then adding both for finding optimal code-rake combination for 20R. Table 4A.1 and Table 4A.2 show different terms giving unique and multiple combinations for 16R and 4R. Table 4A.3 gives different possible vales and rake combiners for each combination of 4R term. Table 4A.4 gives different possible vales and rake combiners for each combination of 16 term. It also gives the code-rake combinations for addition of 16R and 4R codes. Depending upon the available status of the code tree and rake combiners equipped in the UE, optimal code-rake combination can be picked.

Table 4A.1 Illustration of terms with unique and multiple combinations for 16R

Number of non-zero coefficients	Total number of terms	Number of valid terms	Valid terms	Valid terms with unique combinations	Valid terms with multiple combinations
0	1	None	None	None	None
1	5	5	[0,0,0,0,1,0,0,0], [0,0,0,1,0,0,0,0], [0,0,1,0,0,0,0], [0,1,0,0,0,0,0], [1,0,0,0,0,0,0,0]	All valid terms	None
2	10	6	[0,0,1,1,0,0,0,0],[0,1,0,1,0,0,0,0], [1,0,0,1,0,0,0,0],[0,1,1,0,0,0,0,0], [1,0,1,0,0,0,0,0],[1,1,0,0,0,0,0,0]	[0,0,1,1,0,0,0,0], [0,1,0,1,0,0,0,0], [1,0,0,1,0,0,0,0]	[0,1,1,0,0,0,0,0], [1,0,1,0,0,0,0,0], [1,1,0,0,0,0,0,0]
3	10	4	[0,1,1,1,0,0,0,0],[1,0,1,1,0,0,0,0], [1,1,0,1,0,0,0,0],[1,1,1,0,0,0,0,0]	[0,1,1,1,0,0,0,0], [1,0,1,1,0,0,0,0],	[1,1,0,1,0,0,0,0], [1,1,1,0,0,0,0,0]
4	5	1	[1,1,1,1,0,0,0,0]	[1,1,1,1,0,0,0,0]	None
5	1	None	None	None	None

Table 4A.2 Illustration of terms with unique and multiple combinations for 4R

Number of non-zero coefficients	Total number of terms	Number of valid terms	Valid terms	Valid terms with unique combinations	Valid terms with multiple combinations
0	1	0	None	None	None
1	3	3	[0,0,1,0,0,0,0,0], [0,1,0,0,0,0,0,0], [1,0,0,0,0,0,0,0],	All	None
2	3	1	[1,1,0,0,0,0,0,0]	All	None
3	1	0	None	None	None

Table 4A.3 Illustration of terms with unique and multiple combinations for 4R

Valid terms	Code-Rake Combination
[0,0,1,0,0,0,0,0]	{[0,0,1,0,0,0,0,0],1}
[0,1,0,0,0,0,0,0]	{[0,2,0,0,0,0,0,0],2}
[1,0,0,0,0,0,0,0]	{[4,0,0,0,0,0,0,0],4}
[1,1,0,0,0,0,0,0]	{[2,1,0,0,0,0,0,0],3)

Table 4A.4 Code rake combinations for 16R and 20R

Valid terms	Code-Rake Combination	Code-Rake Combination taking addition of 16R and 4R combinations
[0,0,0,0,1,0,0,0]	{[0,0,0,0,1,0,0,0],1}	{[0,0,1,0,1,0,0,0],2} {[0,2,0,0,1,0,0,0],3} {[4,0,0,0,1,0,0,0],5} {[2,1,0,0,1,0,0,0],4}
[0,0,0,1,0,0,0,0]	{[0,0,0,2,0,0,0,0],2}	{[0,0,1,2,0,0,0,0],3} {[0,2,0,2,0,0,0,0],4} {[4,0,0,2,0,0,0,0],6} {[2,1,0,2,0,0,0,0],5}
[0,0,1,0,0,0,0,0]	{[0,0,4,0,0,0,0,0],4}	{[0,0,5,0,0,0,0,0],5} {[0,2,4,0,0,0,0,0],6} {[4,0,4,0,0,0,0,0],8} {[2,1,4,0,0,0,0,0],7}
[0,1,0,0,0,0,0,0]	{[0,8,0,0,0,0,0,0],8}	{[0,8,1,0,0,0,0,0],9} {[0,10,0,0,0,0,0,0],10} {[4,8,0,0,0,0,0,0],12} {[2,9,0,0,0,0,0,0],11}
[1,0,0,0,0,0,0,0]	{[16,0,0,0,0,0,0,0],16}	{[16,0,1,0,0,0,0,0],17} {[16,2,0,0,0,0,0,0],18} {[20,0,0,0,0,0,0,0],20} {[18,1,0,0,0,0,0,0],19}
[0,0,1,1,0,0,0,0]	{[0,0,2,1,0,0,0,0],3}	{[0,0,3,1,0,0,0,0],4} {[0,2,2,1,0,0,0,0],5} {[4,0,2,1,0,0,0,0],7} {[2,1,2,1,0,0,0,0],6}
[0,1,0,1,0,0,0,0]	{[0,4,0,1,0,0,0,0],5}	{[0,4,1,1,0,0,0,0],6} {[0,6,0,1,0,0,0,0],7} {[4,4,0,1,0,0,0,0],9} {[2,5,0,1,0,0,0,0],8}
[1,0,0,1,0,0,0,0	{[8,0,0,1,0,0,0,0],9}	{[8,0,1,1,0,0,0,0],10} {[8,2,0,1,0,0,0,0],11} {[12,0,0,1,0,0,0,0],13} {[10,1,0,1,0,0,0,0],12}
[0,1,1,0,0,0,0,0]	{[0,2,3,0,0,0,0,0],5}	{[0,4,3,0,0,0,0,0],7} {[4,2,3,0,0,0,0,0],9} {[2,3,3,0,0,0,0,0],8}
	{[0,4,2,0,0,0,0,0],6}	{[0,6,2,0,0,0,0,0],8} {[4,4,2,0,0,0,0,0],10} {[2,5,2,0,0,0,0,0],9}
	{[0,6,1,0,0,0,0,0],7}	{[4,6,1,0,0,0,0,0],11} {[2,7,1,0,0,0,0,0],10}
[1,0,1,0,0,0,0,0]	{[4,0,3,0,0,0,0,0],7}	{[8,0,3,0,0,0,0,0],11} {[6,1,3,0,0,0,0,0],10}
	{[12,0,1,0,0,0,0,0],13}	{[12,0,2,0,0,0,0,0],14} {[12,2,1,0,0,0,0,0],15} {[14,1,1,0,0,0,0,0],16}
	{[8,0,2,0,0,0,0,0],10}	{[8,2,2,0,0,0,0,0],12} {[10,1,2,0,0,0,0,0],13}

[1,1,0,0,0,0,0,0]	{[2,7,0,0,0,0,0,0],9}	{[6,7,0,0,0,0,0,0],13}
	{[4,6,0,0,0,0,0,0],10}	{[8,6,0,0,0,0,0,0],14}
	{[6,5,0,0,0,0,0,0],11}	{[6,5,1,0,0,0,0,0],12} {[10,5,0,0,0,0,0,0],15}
	{[8,4,0,0,0,0,0,0],12}	{[8,4,1,0,0,0,0,0],13} {[12,4,0,0,0,0,0,0],16}
	{[10,3,0,0,0,0,0,0],13}	{[10,3,1,0,0,0,0,0],14} {[14,3,0,0,0,0,0,0],17}
	{[12,2,0,0,0,0,0,0],14}	
	{[14,1,0,0,0,0,0,0],15}	{[14,1,1,0,0,0,0,0],16}
[0,1,1,1,0,0,0,0]	{[0,2,1,1,0,0,0,0],4}	{[4,2,1,1,0,0,0,0],8} {[2,3,1,1,0,0,0,0],7}
[1,0,1,1,0,0,0,0]	{[4,0,1,1,0,0,0,0],6}	{[6,1,1,1,0,0,0,0],9}
[1,1,0,1,0,0,0,0]	{[2,3,0,1,0,0,0,0],6}	{[6,3,0,1,0,0,0,0],10}
	{[4,2,0,1,0,0,0,0],7}	
	{[6,1,0,1,0,0,0,0],8}	
[1,1,1,0,0,0,0,0]	{[2,1,3,0,0,0,0,0],6}	
	{[2,3,2,0,0,0,0,0],7}	{[6,3,2,0,0,0,0,0],11}
	{[4,2,2,0,0,0,0,0],8}	
	{[6,1,2,0,0,0,0,0],9}	
	{[2,5,1,0,0,0,0,0],8}	{[3,6,1,0,0,0,0,0],10}
	{[4,4,1,0,0,0,0,0],9}	
	{[6,3,1,0,0,0,0,0],10}	{[10,3,1,0,0,0,0,0],14}
	{[8,2,1,0,0,0,0,0],11}	
	{[10,1,1,0,0,0,0,0],12}	
[1,1,1,1,0,0,0,0]	{[2,1,1,1,0,0,0,0],5}	

CHAPTER 5

Compact single code assignment schemes

5.1 Introduction

There are two ways to minimize the blocking probability in single code assignment schemes. In the first case, the reassignments are applied to the existing busy codes so that the vacant codes can be located. The WCDMA system with code reassignments require to transmit large signaling overhead. This is required to transmit the information of code locations prior to code reassignments and after the code reassignments. In the second case the code assignments are done in most compact form such that the probability of code blocking due to scattered vacant codes (also known as external fragmentation) becomes very small. No extra overhead is required to transmit the information of reassignments. The chapter discusses compact schemes without reassignments.

5.2 Priority Based Code Assignment (PBA) Scheme

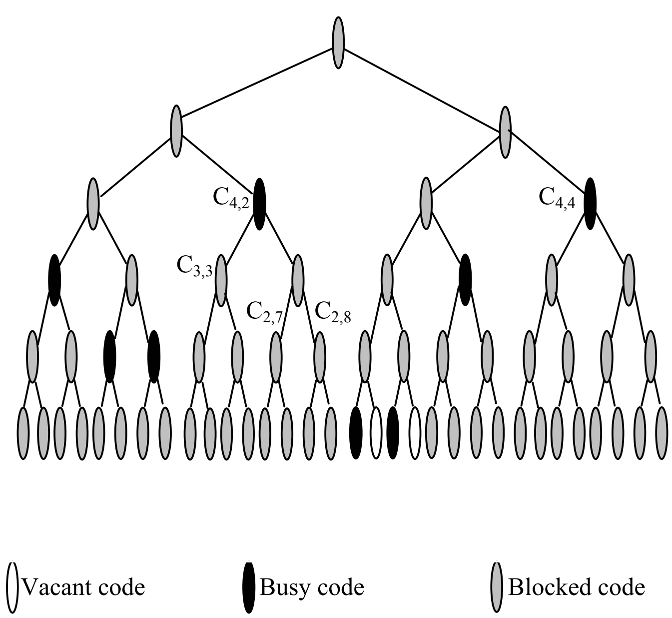
5.2.1 Description

In the PBA code assignment scheme we divide L (8 in WCDMA) classes into P priority (real time) classes and L-P non priority (best effort) classes. The rate of the priority class x is 2^{x-1}R, $x \in \{1,2,...,P\}$. The fundamental idea is to utilize higher layer codes (corresponding to best effort type classes) to handle lower rates (corresponding to real time calls). So QoS provision is made due to better treatment for real time calls compared to best effort calls. For the best effort traffic classes, we decide threshold for number of busy codes denoted by H_n, $n \in \{P+1, P+2,...,L\}$. If a new user with rate 2^mR, $\{ m < P \}$ arrives, the availability of vacant code is checked in layer m. If vacant code is available it is assigned to the incoming user. All of its ancestors and descendants are blocked according to blocking procedure discussed in Table 2.1. If there is no vacant code we check the threshold for busy codes in the layers P+1 to L starting from layer P+1. If the threshold of layer l i.e. $H_l, l \in \{P+1, P+2,....,L\}$ is not exceeded, we randomly pick a busy code BC_l in layer l. We divide the data rate of the busy user (BU_l)

Table 5.1 Bandwidth division of busy codes in best effort traffic classes to handle real time call

Class	Rate	Category	Bandwidth division
1	$2^0R=R$	Real time	$2^{L-1}R, 2^{L-2}R, \ldots .R, \underline{R}$
2	2^1R	Real time	$2^{L-1}R, 2^{L-2}R, \ldots .2R, \underline{2R}$
….	….	….	….
P	$2^{P-1}R$	Real time	$2^{L-1}R, 2^{L-2}R, \ldots .2^{P-1}R, \underline{2^{P-1}R}$
P+1	2^PR	Best effort	Not applicable
P+2	$2^{P+1}R$	Best effort	Not applicable
….	….	….	….
L	$2^{L-1}R$	Best effort	Not applicable

corresponding to the BC_l into subsets $2^{l-1}R, 2^{l-2}R, \ldots, 2^mR, \underline{2^mR}$. All the rates of BU_l except underlined are handled by the descendants of BC_l. The code with the underline capacity 2^mR is assigned to the incoming user. The overall transmission rate of the



Layer	Bandwidth	SF
6	32 R	1
5	16 R	2
4	8 R	4
3	4 R	8
2	2 R	16
1	1 R	32

Figure 5.1 Illustration of the PBA scheme

system is same but the number of calls in progress increases. The bandwidth partition for busy codes in the best effort classes to handle real time calls is shown in the Table 5.1.

The proposed scheme requires more rake combiners at the receiver end as compared to the schemes which do not incorporate the rate division features. The PBA scheme is explained in Figure 5.1. Consider the OVSF-CDMA system with six layers. The layers 1, 2, 3 are for priority/real time calls and layers 4, 5, 6 are for non real/ best effort calls. Assume the threshold for number of busy trees in layer 4, 5, 6 is 3, 2, 1. If a new user with rate 2*R* arrives it checks the availability of vacant code in layer 2. There is no vacant code in layer 2 and the PBA scheme start checking the busy code threshold from layer 4 to 6. The number of busy codes in layer 4 is 2, which is less than the threshold value of 3 codes. The code $C_{4,2}$ is randomly picked. The rate of the user corresponding to code $C_{4,2}$ is 8R. We divide the rate into four parts 4R, 2R, 2R. The codes to handle 4*R* and 2*R* data rate are $C_{3,3}$ and $C_{2,7}$. The code $C_{2,8}$ is assigned to the incoming real time call of rate 2R.

5.2.2 Flowchart and Algorithm

The flowchart of the PBA scheme is shown in Figure 5.2. The algorithm is outlined below

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.

3. If the rate of new call with rate 2^mR ($m<P$) is more than the available capacity of the code tree, call is discarded. Otherwise the availability of the vacant code is checked in layer m.

4. If vacant code is available, it is assigned to the call. If vacant code is not available the threshold for non-priority calls is checked from layer P+1 to L.

5. If the threshold is not exceeded, the busy code rate is broken into smaller sub rates such that the code corresponding to new call becomes vacant as discussed. The code is used by the new call and remaining sub codes are used by the call already in progress.

6. If the threshold for all the non-priority classes is exceeded, the call is discarded.

7. Go to the step 2.

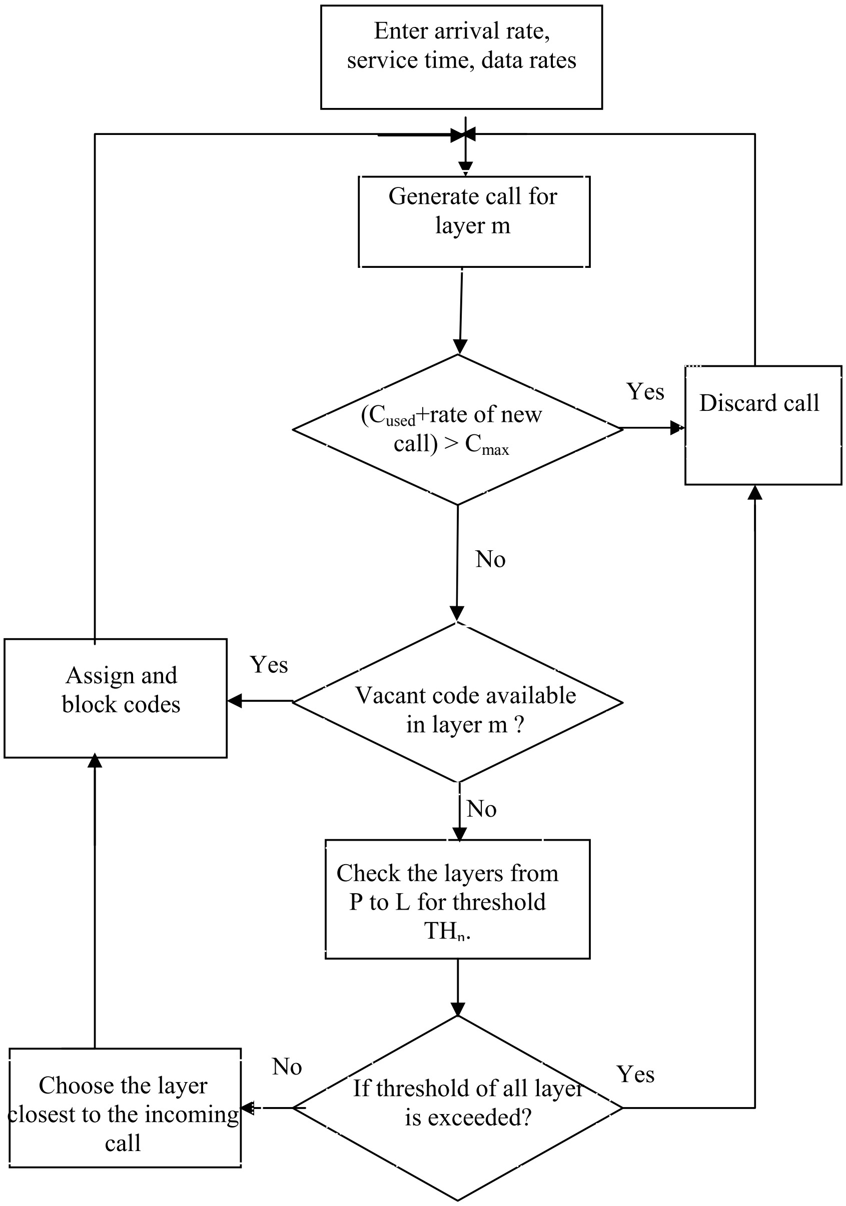


Figure 5.2 Flowchart of PBA scheme

5.2.3 Input Parameters

- Call arrival process is Poisson with mean arrival rate λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value $1/\mu$ =1 units of time.
- Possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes

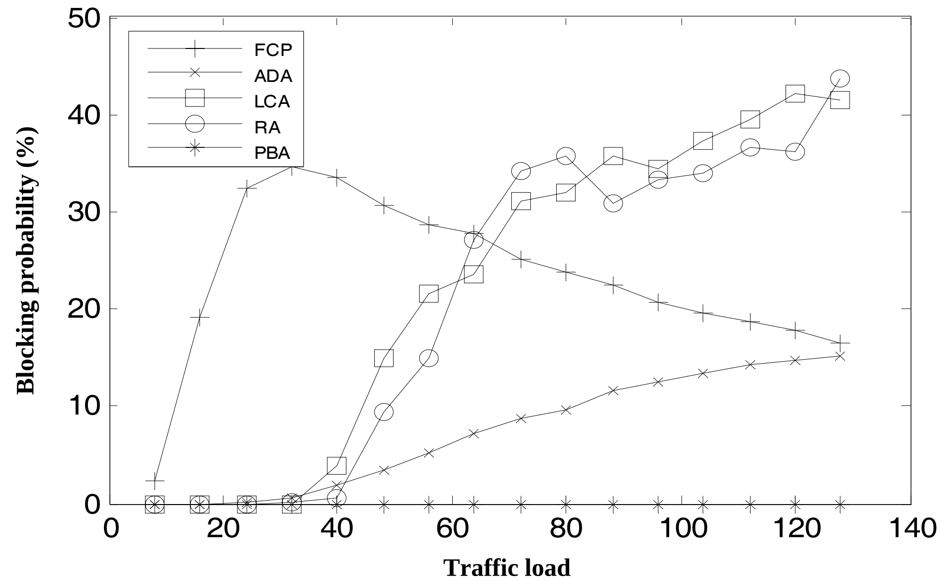


Figure 5.3 Blocking probability vs traffic load for uniform distribution

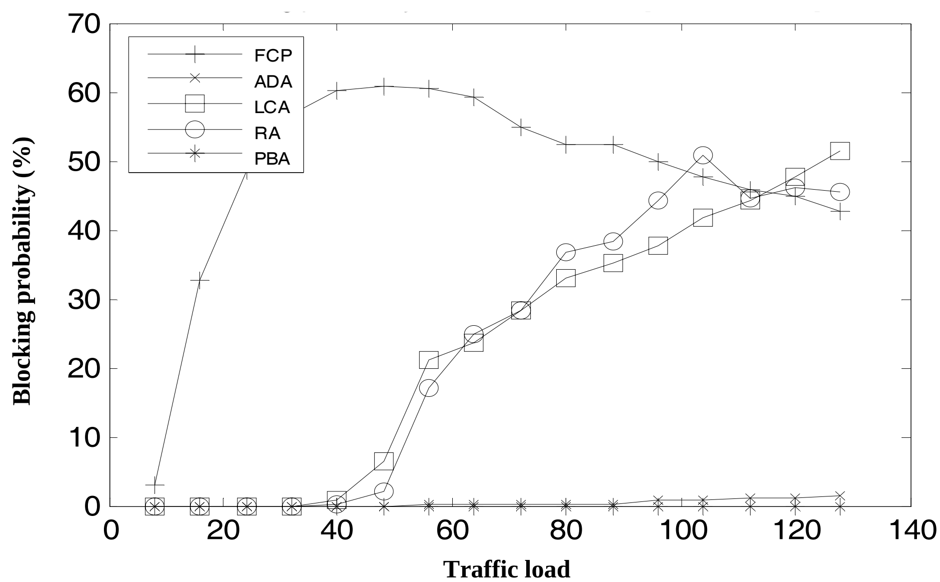


Figure 5.4 Blocking probability vs traffic load for more real time calls

- The rates R, 2R are considered as real time calls and rate 4R, 8R are considered as best effort data.
- Total number of trees T is 16.

5.2.4 Results

We compare the performance of *PBA* scheme with the performance of Random Assignment (RA), Leftmost Code Assignment (LCA), Fixed Code Assignment (FCP) and Adaptive Code Assignment (ADA) schemes discussed earlier. We consider probabilities for different class users as (p_1, p_2, p_3, p_4), where p_1, p_2, p_3 and p_4 are the probabilities of arrival rate R, 2R, 4R and 8R users. We consider two different distributions of arrival classes. In the first case traffic load is uniform for the four arrival classes and in the second case, real time traffic rates dominates the traffic load. The simulation is done for 5000 users and result is the average of 10 simulations. Figure 5.3-5.4 shows the performance improvement due to reduction in blocking probability of real time calls.

5.3 Compact code assignment (CCA) scheme

5.3.1 Description

Table 5.2 Illustration of number of codes in each group, where the number of groups is 8

Layer	No. of codes in each group	Maximum used capacity
1	16	16R
2	8	16R
3	4	16R
4	2	16R
5	1	16R

In the proposed scheme, we divide the leaves (128 codes in layer 1) into 8×2^n, $n\in[0,4]$ groups. Higher is the value of n, more is the number of groups making code tree compact for assignment of low data rates. The division is performed to make the code assignment most compact. The number of codes in each layer for 8 groups (corresponding to n=0) is given in Table 5.2. When a new call arrives with the code requirement from any of the layers 1 to 5, the most compact group is chosen for code assignment. For a code $C_{5,n}$, the code group contains codes given in Equation (5.1).

$$\begin{array}{ll} C_{4,2n-1},\ C_{4,2n} & \text{in layer 4} \\ C_{3,4n-3},\ldots,\ C_{3,4n} & \text{in layer 3} \\ C_{2,8n-7},\ldots,\ C_{2,8n} & \text{in layer 2} \\ C_{1,16n-15},\ldots,\ C_{1,16n} & \text{in layer 1} \end{array} \tag{5.1}$$

5.3.2 Flowchart and Algorithm

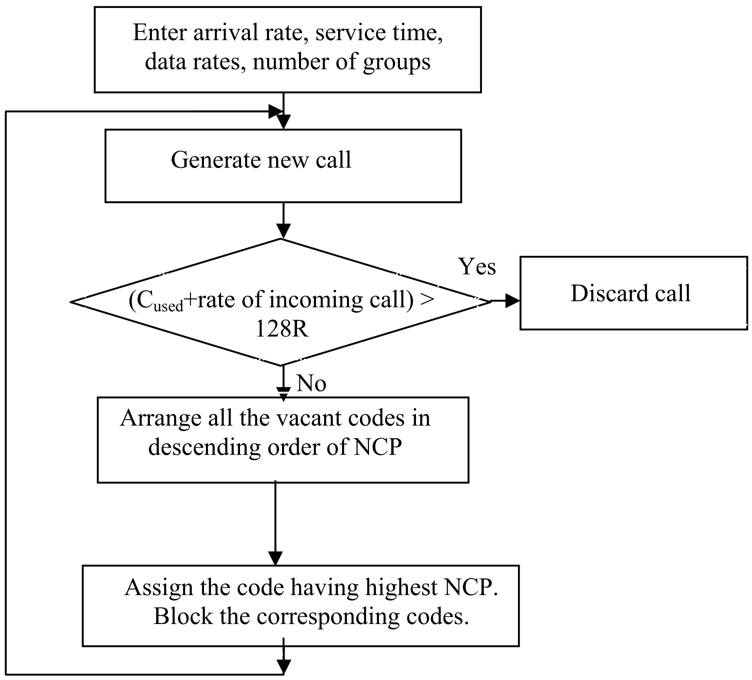


Figure 5.5 Flowchart of CCA scheme

The flowchart of the CCA scheme is shown in Figure 5.5. The algorithm for assignment scheme considering 8 groups in layer 5 is given below,

- Input parameters such as arrival rate, call duration and number of layers are entered.
- For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.
- For a new call requiring code from layer from layer l, $l \in [1,5]$, possible vacant codes are listed.
- For each vacant code, find the group to which the code belongs. Find the neighbor capacity (NCP) for the vacant code in its associated group. Neighbor capacity for code $C_{l,n}$ is defined sum of capacities of all the busy descendants of parent of the code $C_{l,n}$ in layer 5.

- Pick the code from the most congested code group (group with highest neighbor capacity). If two or more codes from same or different groups have the same neighbor capacity, any of them can be used for assignment.

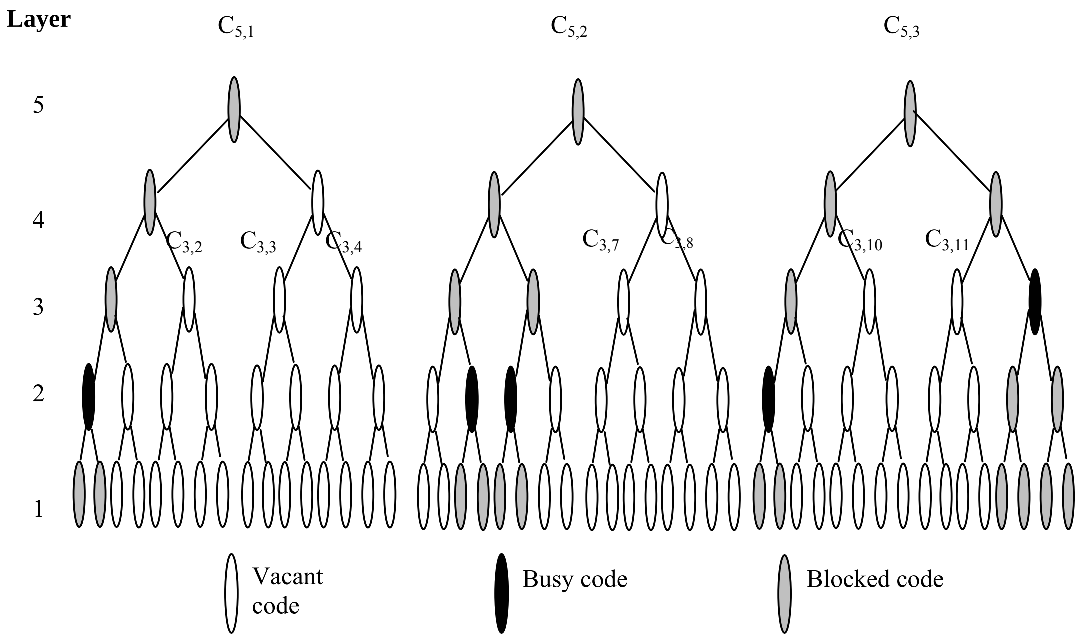


Figure 5.6 Illustration of CCA scheme

The above procedure leads to the minimum external fragmentation of the remaining capacity which makes the code assignment most compact. The higher data rates (e.g. rates corresponding to layer 6, 7 and 8 in 8 code groups example) are treated like leftmost code assignment scheme. The proposed assignment scheme is explained with the example shown in Figure 5.6. The total number of groups is assumed to be 8, so that each group has 16 leaves. We consider five layers in the OVSF-CDMA system consisting of 3 trees of capacity 16R each. Assume the status of the code tree before the arrival of new call as shown in Figure 5.6. If a new user with the requirement of layer 3 code arrives, there are large numbers of vacant code alternatives. The codes $C_{3,2}$, $C_{3,3}$ and $C_{3,4}$ belongs to the same group with neighbor capacity of 2R each. The neighbor capacity of $C_{3,7}$ and $C_{3,8}$ is 4R each. Similarly the neighbor capacity of $C_{3,10}$ and $C_{3,11}$ is 6R. The neighbor capacity of $C_{3,10}$ and $C_{3,11}$ is maximum and any of the two can be assigned to the incoming call.

5.3.3 Input Parameters

- Call arrival process is Poisson with mean arrival rate λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value $1/\mu$ =1 units of time.
- Possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes
- Total number of code groups considered is 16 to make maximum capacity 128R (equal to the capacity of WCDMA systems).

5.3.4 Results

We consider event driven simulation for getting results. The possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes. Simulation results are presented to show the new call blocking probability of the proposed CCA scheme. We compare the blocking probability of CCA scheme with the blocking probability of random assignment (RA), leftmost code assignment (LCA) and fixed code partitioning (FCP) schemes discussed earlier. The probability distribution is denoted by (p_1, p_2, p_3, p_4), where p_1, p_2, p_3 and p_4 are the probabilities of arrival rate R, 2R, 4R and 8R users. Three traffic arrival distributions are considered. In the first case, all the four classes have uniform distribution (Figure 5.7.). In the second case, the probability of arrival of real time calls (R, 2R for simulation results) is more compared to non-real time calls (Figure 5.8.). In the third case (Figure 5.9.), non-real time calls (4*R*, 8*R* for simulation results) dominate the traffic. The simulation is done for 5000 users and result is the average of 10 simulations. The results show that for all kinds of traffic compact code assignment scheme provides reduction in new call blocking.

5.4 Next Code Precedence High (NCPH) Code Assignment Scheme

5.3.1 Description

When the new call arrives the vacant code is assigned to it. All of its ancestors and descendants are blocked as discussed earlier. In addition, the code next to the assigned code as well as all of its ancestors and descendants are given a two dimensional *precedence number* (*x,y*), where '*x*' is the *layer number* and '*y*' is the *vacant code priority number*. The *precedence number* is to be used by next incoming calls. At any

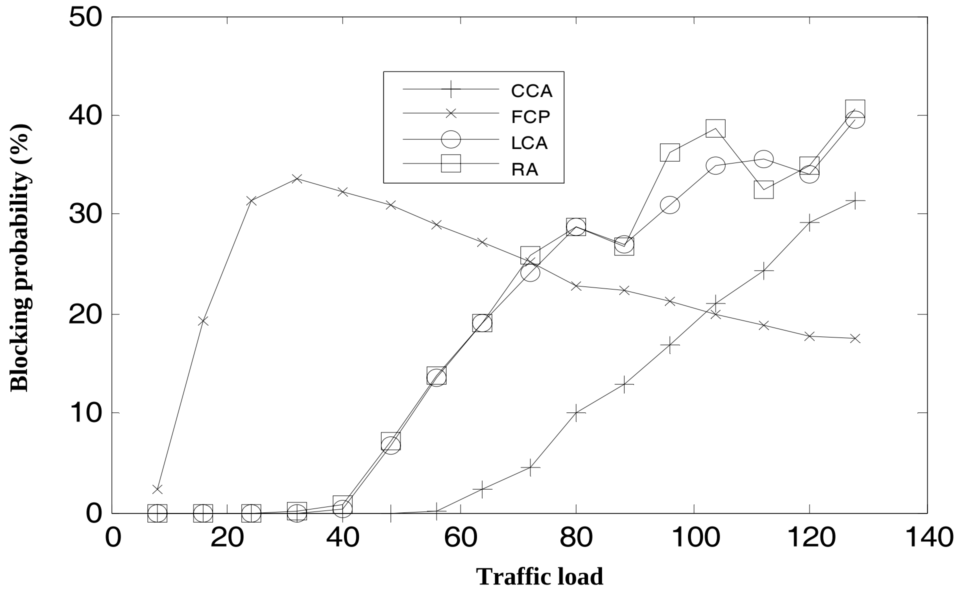


Figure 5.7 Blocking probability vs traffic load for uniform distribution

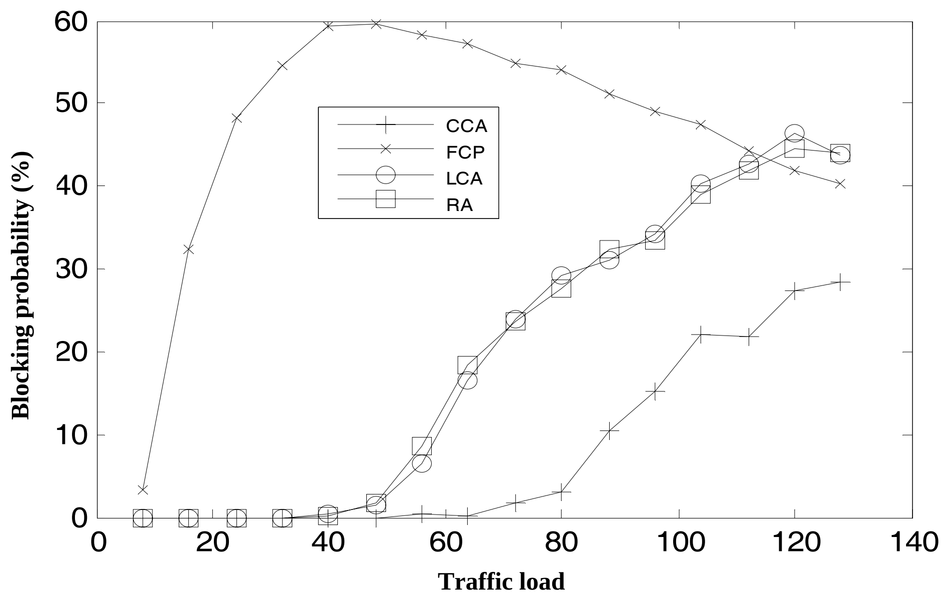


Figure 5.8 Blocking probability vs traffic load for more real time calls

time, assume that the code tree is vacant. When a new call occupies code $C_{l,n}$, the codes blocked and the codes which are given *precedence number* are given in Figure 5.10.

The vacant codes are listed according to the *precedence number* used. The list is prepared for every layer and updated for every new call. If two or more codes in a layer

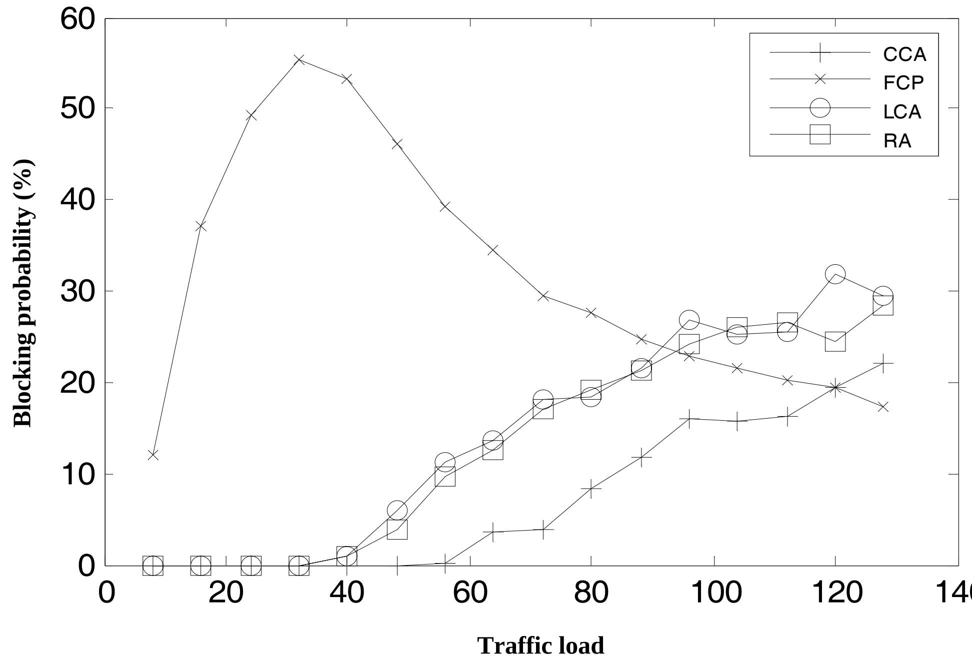


Figure 5.9 Blocking probability vs traffic load for more non-real time calls

have same *vacant code priority number*, any of them can be used for assignment. When a code is used for assignment, *precedence numbers* (*priority numbers*) of codes and all of its ancestors and descendants is given arbitrary large value so that they are not candidates for code assignment procedure. When the call is completed for a code, its *priority number* is made higher than the highest *vacant code priority number*. So the code *precedence number* is modified for every code assignment and call completion. The *precedence number* has following properties

- Initially when the code tree is vacant, the Code $C_{l,n}$ is represented by two dimensional *precedence number* (l,n).
- When the code is occupied by the call, its ancestors and descendants are given arbitrary large value of *priority number* say 10000, signifying that the codes are in use.
- When the call using code $C_{l,n}$ is completed, its ancestors and descendants are given *precedence number* higher than the highest *precedence number* in the code layer (*e.g.* 129{2^7+1} for layer 1, 65{2^6+1} for layer2 and so on.)
- If two or more codes have same (l,n) number, any of them can be used for new call.

Codes Blocked

Descendants

$C_{l-1,2n-1}$, $C_{l-1,2n}$ in layer l-1

$C_{l-2,4n-3}$,…., $C_{l-2,4n}$ in layer l-2

………………………………

$C_{l,2^{l-1}n-2^{l-1}+1},\ldots,C_{l,2^{l-1}n}$ in layer 1

Ancestors

$C_{l+1,\left\lceil \frac{n}{2} \right\rceil}$ in layer l+1

$C_{l+2,\left\lceil \frac{n}{4} \right\rceil}$ in layer l+2

……………………………….

$C_{8,\left\lceil \frac{n}{2^{8-l}} \right\rceil}$ in layer 8

Codes with Precedence number

$C_{l,n}$, $C_{l,n+1}$ in layer l

$C_{l-1,2n+1}$, $C_{l,2n+2}$ in layer l-1

$C_{l-2,4n+1}$, $C_{l-2,4n+4}$ in layer l-2

……………………………….

$C_{1,2^{l-1}n+1},\ldots,C_{1,2^{l-1}n+2^{l-1}}$ in layer 8

Figure 5.10 Illustration of blocked codes and the codes which are assigned precedence number corresponding to busy code $C_{l,n}$.

The assignment scheme is illustrated in Figure 5.11. The vacant code tree with five layers is considered. For simplicity we did not consider the precedence number of the vacant codes. Let the three calls with rate 2R, 4R and 4R arrives in sequence. The code assignment and precedence ordering for three calls is shown in Figure 5.11(a), 5.11(b) and 5.11(c).

5.4.2 Flowchart and Algorithm

The flowchart of the NCPH scheme is shown in Figure 5.12. The algorithm is outlined as follows

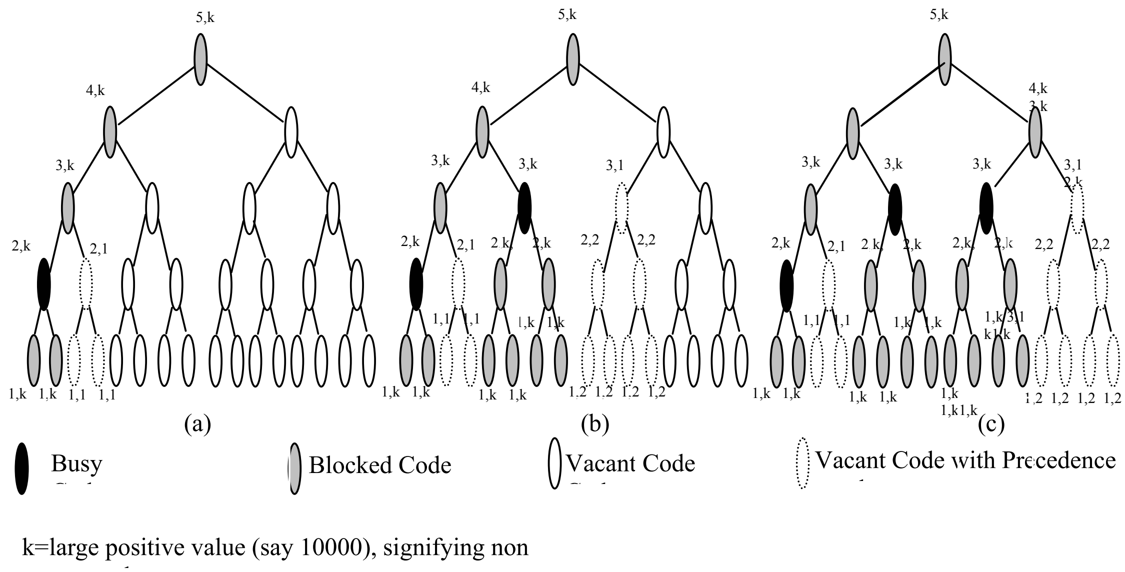


Figure 5.11 Illustration of NCPH code assignment scheme. Figure 5.11 shows code assignment, blocking and precedence number assignment for first 2R rate call arrival. Figure 5.11(b) and (c) illustrates the assignment, blocking and precedence number assignment for second (Rate 4R) call and third (Rate 8R) call.

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.

3. If the system has capacity, the vacant code with the lowest precedence number is used for assignment. All the ancestors and descendants of the code are given a constant large value so that they are not the candidates for assignment.

4. Go to step 2.

5.4.3 Input Parameters

- Call arrival process is Poisson with mean arrival rate λ =1-128 calls/ unit time.
- Call duration is exponentially distributed with a mean value $1/\mu$ =1 units of time.
- Possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes.
- Total number of codes in layer 4 is 16 making maximum capacity of the system 128R.

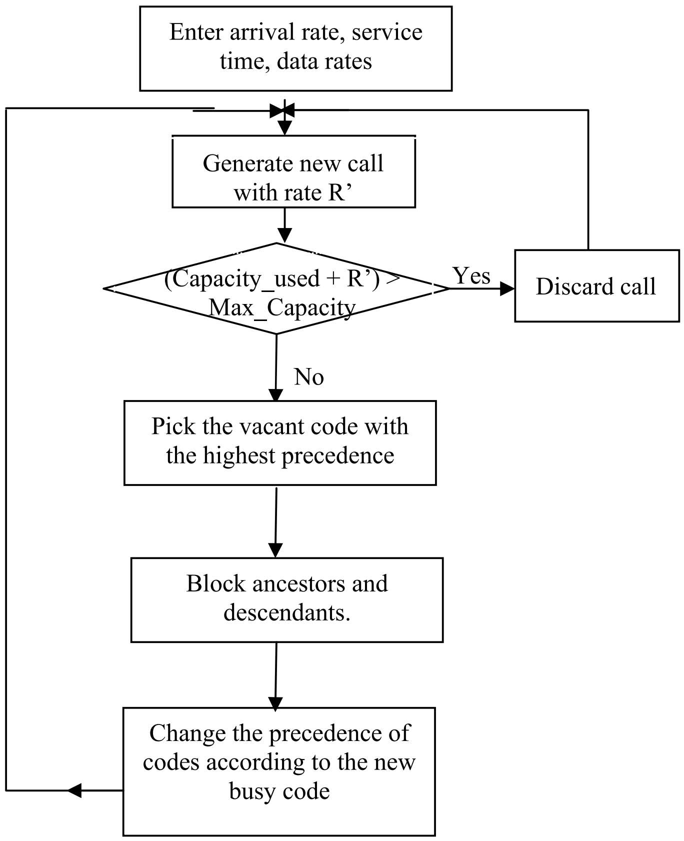


Figure 5.12 Flowchart for simulation model

5.4.4 Results

Simulation results are demonstrated to show the reduction in call blocking probability in *NCPH* scheme. The call blocking in *NCPH* scheme is compared with the call blocking of Random Assignment (*RA*), Leftmost Code Assignment (*LCA*), Fixed Set Partitioning (*FSP*) and Dynamic Code Assignment (*DCA*) schemes discussed earlier. The probabilities for different class users are denoted by (p_1,p_2,p_3,p_4), where p_1,p_2,p_3 and p_4 are the probabilities of arrival rate R,2R,4R and 8R users. We consider three different distributions of arrival classes. In the first case traffic load is uniform (Figure 5.13) for the four arrival classes. In the second case, non-real time traffic rates (higher data rates) (Figure 5.14) dominates the traffic load and in the third case real time users (lower data rates) (Figure 5.15) dominates the traffic. The simulation is done for 5000 users and result is the average of 10 simulations. Simulation results shows that the call blocking in *NCPH* code assignment scheme is less compared to *FSP*, *LCA* and *RA* assignment schemes and is more than *DCA* scheme.

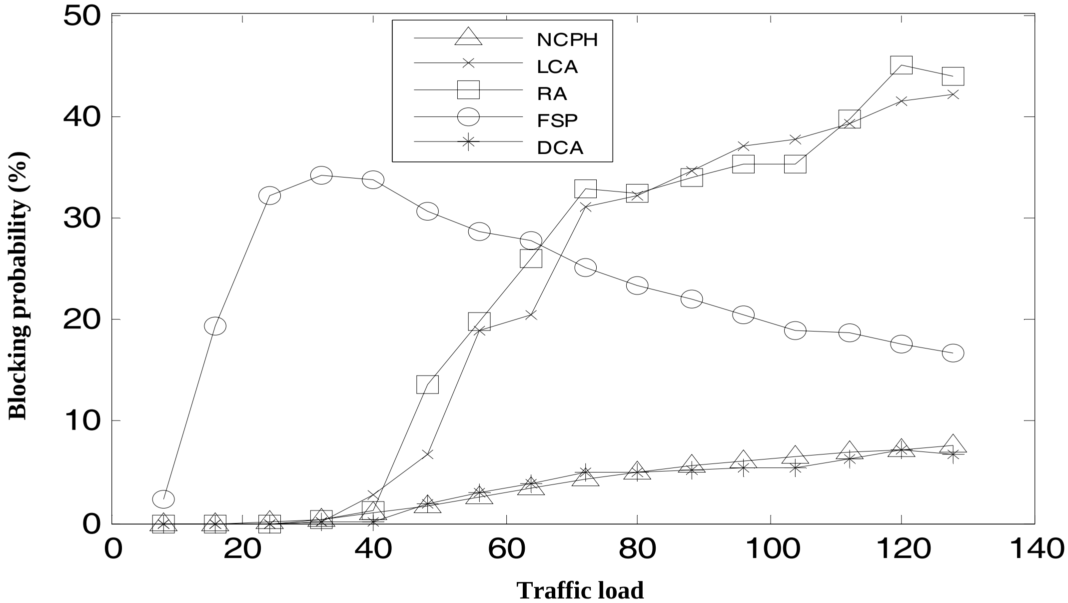


Figure 5.13 Blocking probability vs traffic load for uniform distribution

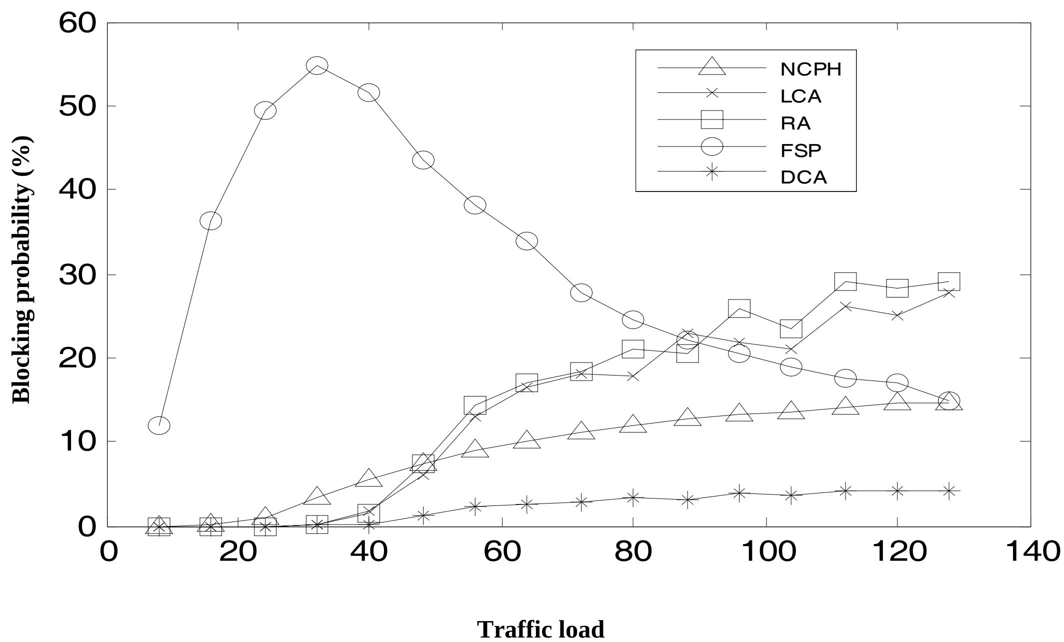


Figure 5.14 Blocking probability vs traffic load for more non real time calls

5.5 Summary

In this chapter three compact code assignment schemes are proposed to reduce the code blocking. The PBA scheme use vacant code capacity from the busy code of type best effort to handle the real time calls. The scheme is suited when the distribution of the

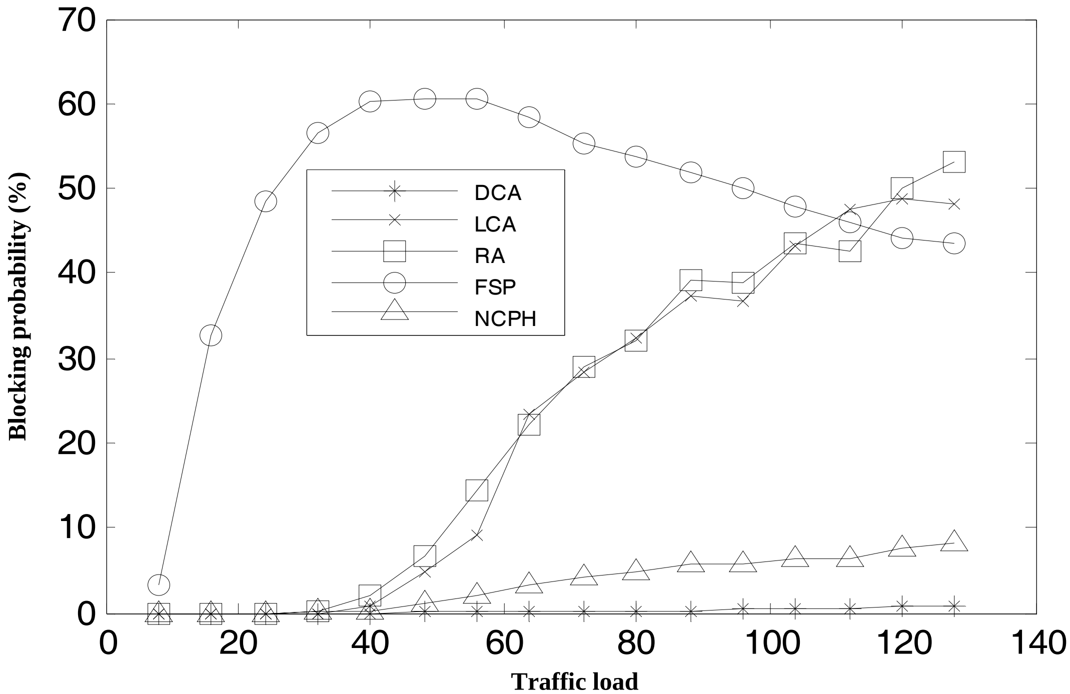


Figure 5.15 Blocking probability vs traffic load for more real time calls

arrival rates is not uniform and system must have good QoS requirements. The CCA scheme makes the code tree crowded with busy code very close to each other. This makes lot of higher layer codes free to handle higher rate calls. The NCPH scheme uses look up table to find the best candidate code for the new call such that the remaining capacity of the tree is least fragmented.

CHAPTER 6

Miscellaneous code assignment schemes

6.1 Introduction

The chapter describes a number of code assignment schemes independent of the properties of code tree. As discussed, the WCDMA downlink has the 8 layer OVSF code tree with one code in the layer 8. Using standard Walsh procedure, starting with length one code (chip rate is same as data rate), the number of codes with length four are 4. In the current WCDMA system, only one code with length one is used. So, we can extend the size of the code tree from 8 layers to 10 layers increasing the codes capacity 4 times. If we have enough vacant codes available, the code rate wastage can be minimized to zero by dividing the higher rates into smaller quantize rates. Here the code blocking can be reduced to zero.

The OVSF code tree art the UE is not utilized fully as there is single UE to use full OVSF code tree. So we can utilize the code tree at the UE for the BS. The BS code tree in this case is only used for control signals before call set up. The blocking problem does not exist at all. The time multiplexing can be used to use the capacity of single code for number of users.

6.2 Code Tree Extension

6.2.1 Description

Using standard Walsh code procedure [7], starting with single bit, the number of codes in the 1st and 2nd step are 2(two bit size) and 4(four bit size). So the number of codes with the spreading code 4 are 4([1,1,1,1], [1,1,-1,-1], [1,-1,1,-1] and [1,-1,-1,1]) respectively as shown in Figure 6.1. Therefore corresponding to the SF 4, there are 4 orthogonal codes. In WCDMA systems used so far, we uses one code out of these 4 codes in layer 8. In the proposed scheme, we use all four possible codes in layer 8. The capacity of system and the number of codes in each layer is increased 4 times. This is equivalent to using a 10 layer OVSF code tree with codes in layer 10 and 9 unused. The extension of the code tree is shown in Figure 6.1. The current WCDMA systems uses only one code (say

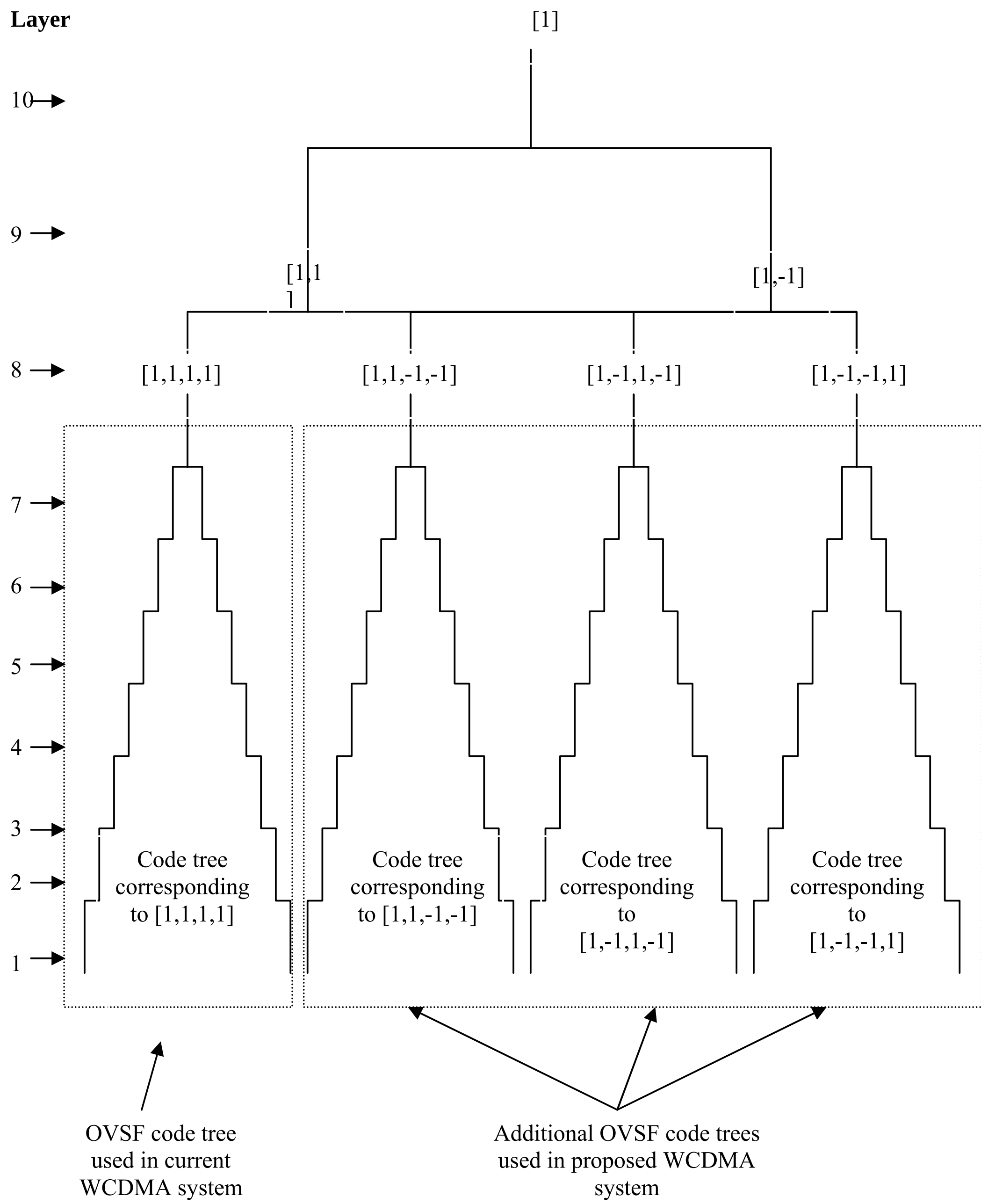


Figure 6.1 Illustration of OVSF code tree extension. In the current WCDMA system only one code with SF 4 (e.g. code [1,1,1,1] shown above)is used. In the proposed design, we uses three additional codes with SF 4 (orthogonal to [1,1,1,1]). The codes are generated using Walsh encoding.

[1,1,1,1]) in layer 8 and extend the tree till layer 1. In the proposed design, we add three more orthogonal codes ([1,1,-1,-1], [1,-1,1,-1] and [1,-1,-1,1]). The extension does not add complexity in UE because, for every call single code (requiring single rake combiner

as already available in present WCDMA systems) is used from any of the four code trees.

6.2.2 Flowchart and Algorithm

The flowchart of the code tree extended OVSF-CDMA scheme is shown in Figure 6.2. The algorithm is outlined below

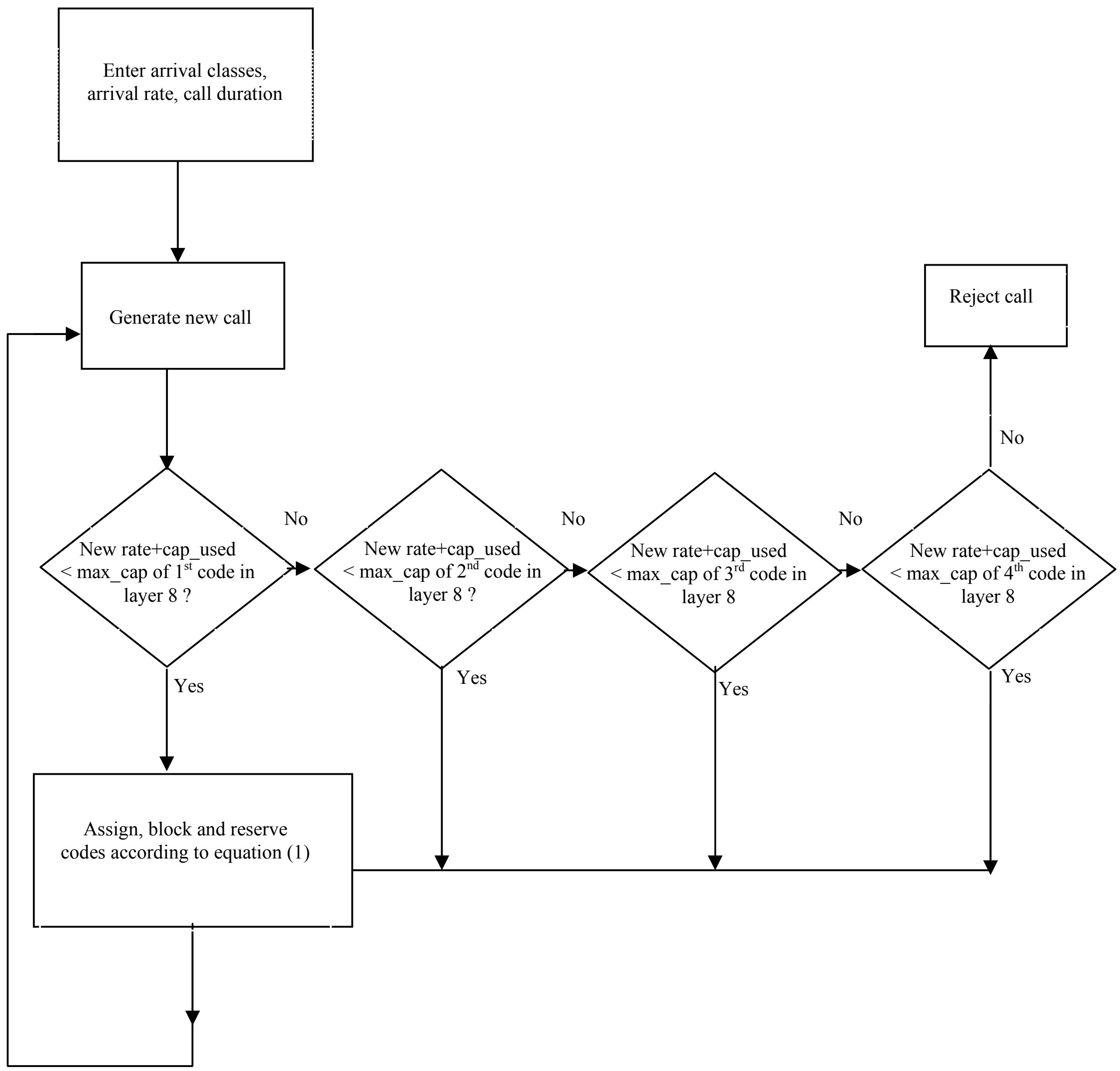


Figure 6.2 Flowchart for extended OVSF code tree assignment

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. For each new call, capacity check is performed to verify that whether new call can be handled by the 1st code or its children in the 8-layer OVSF code tree or not.
3. If the rate of new call is more than the available capacity of the code tree, capacity check is performed for the second code and its children. The procedure is repeated till we reach 4th code.
4. If the rate can not be handled even with the 4th code, the new call is discarded otherwise the code assignment, code blocking is done.
5. Go to the step 2.

6.2.3 Input Parameters

- The call arrival process is assumed to be *Poisson* with mean arrival rate, λ varying from 1 to 128 calls/ unit time.
- The call duration is exponentially distributed with a mean value, $1/\mu$ is 1 units of time.
- The possible OVSF code rates considered are R, 2R, 4R and 8R corresponding to four different arrival classes.
- The total number of codes in layer 4 is 16 for all the previous schemes and is 64 for the design proposed.

6.2.4 Results

We consider event driven simulation for getting results. Simulation results are plotted for the new call blocking in the proposed extended OVSF code tree system. We compare the call blocking probability of Code tree Extended scheme named as 4-OVSF (indicating the extension by 4 times) scheme with the call blocking of random assignment (RA), leftmost code assignment (LCA), fixed set assignment (FSP) and dynamic code assignment (DCA) schemes discussed earlier. The probabilities for different class users are denoted by (p_1, p_2, p_3, p_4), where p_1, p_2, p_3 and p_4 are the probabilities of arrival rate R, 2R, 4R and 8R users. We consider three different distributions of arrival classes. In the first case traffic load is uniform (Figure 6.3.) for the four arrival classes. In the second case, non-real time traffic rates (higher data rates 4R and 8R) (Figure 6.4.) dominates the traffic load and in the third case real time users (lower data rates R and 2R) (Figure 6.5.) dominates the traffic. The simulation is done

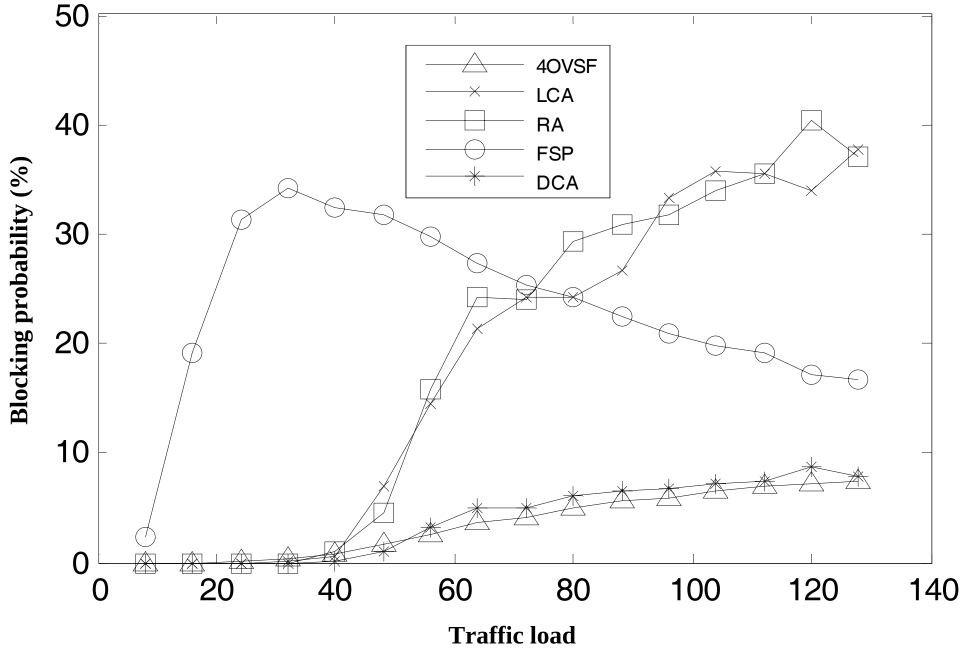


Figure 6.3 Blocking probability vs traffic load for uniform distribution

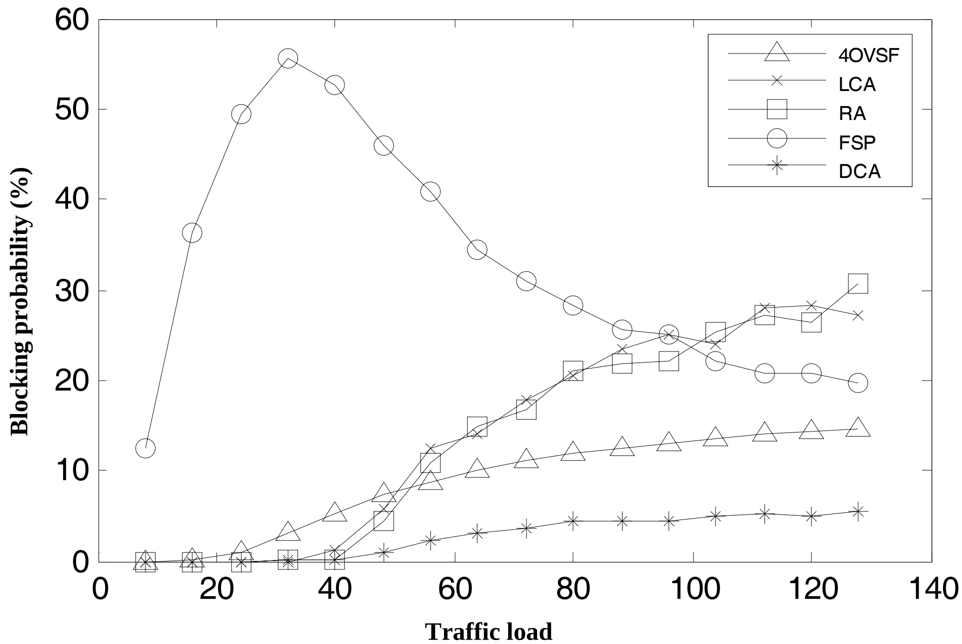


Figure 6.4 Blocking probability vs traffic load for more non real time calls

for 5000 users and result is the average of 10 simulations. Results show that the call blocking is far less in the proposed design compared to RA, LCA and FSP schemes for

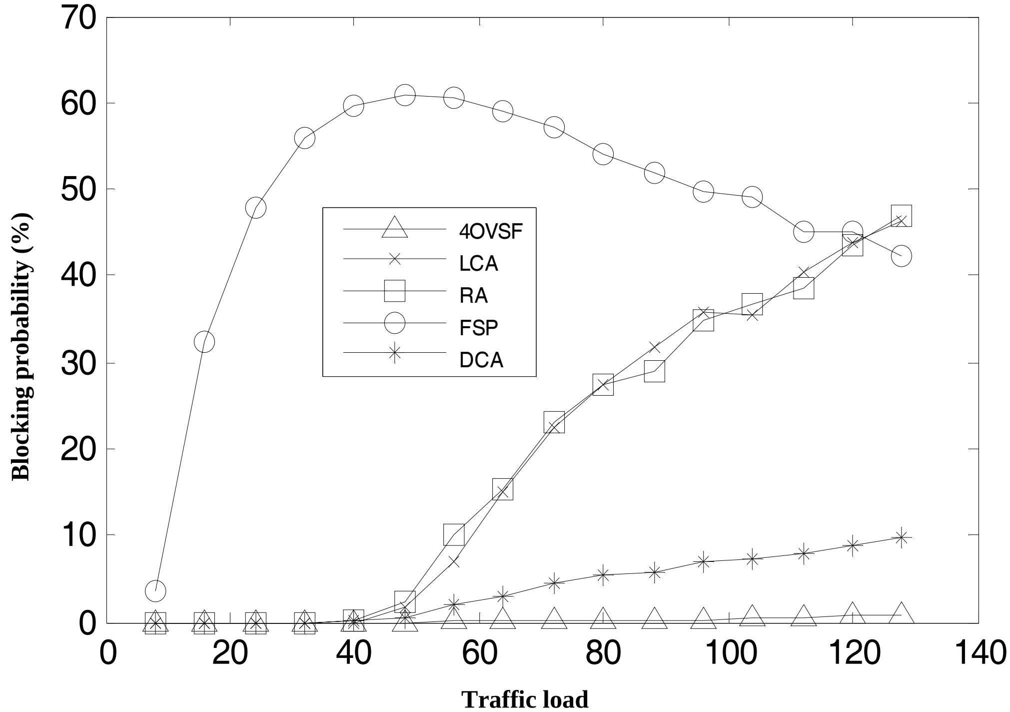


Figure 6.5 Blocking probability vs traffic load for more real time calls

all types of traffic. Call blocking is even lesser than the DCA scheme except for the case of non real time calls dominating scenario.

6.3 Bandwidth Division Assignment (*BDA*) scheme

6.3.1 Description

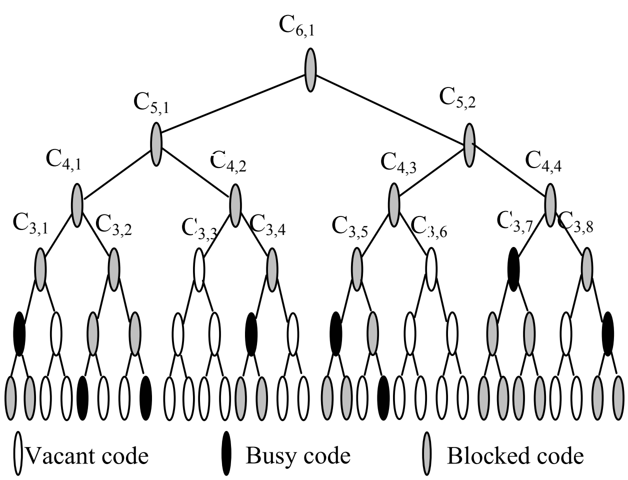
In the proposed assignment scheme initially code is assigned similar to the *LCA* scheme. When the code tree is too fragmented causing unavailability of vacant code for higher data rates, we divide the input data rate 2^lR into one of 2, 4, ..., 2^{l-1} parallel groups of rate 1/2, 1/4, …, $1/2^{l-1}$ depending upon the available capacity of the layer. If rate 2^l is not handled by layer l due to code blocking, we check layer l-1. If the layer l-1 has vacant capacity at least equal to 2^l we divide the input data rate into two groups of rate 2^{l-1}R each and two vacant codes from layer l-1 are assigned to it. If the vacant capacity in layer l-1is less than 2^lR, we go to the layer l-1 and so on till we find a layer with available capacity at least 2^lR. So depending upon the availability of codes we can divide the rate into smaller groups. The code blocking can be made as small as zero using the proposed assignment scheme. The number of channels required increases exponentially as we

Table 6.1 Illustration of rate handling using codes of different layers

Rate	Layer	Number of codes required	Number of channels required
$R^{`}=2^{l}R$	1	2^{l-1}	2^{l-1}
	2	2^{l-2}	2^{l-2}
	….	….	….
	l-1	2	2
	l	1	1

divide the bandwidth from layer l down to leaf code. Table 6.1 shows the number of codes required in different layers for handling data rate 2^{l}R. The proposed bandwidth division scheme is independent of the arrival class distribution.

For illustration of assignment scheme, consider the tree shown in Figure 6.6. As explained earlier the code tree cannot handle user with data rate 8R directly. We start



Layer	Bandwidth	SF
6	32 R	1
5	16 R	2
4	8 R	4
3	4 R	8
2	2 R	16
1	R	32

Figure 6.6 OVSF code tree with six layers

traversing the tree downwards till we reach to a layer whose vacant capacity is at least 8R. As we see the layer 4 has two vacant codes $C_{3,3}$ and $C_{3,6}$ making vacant capacity of 8 units. So the user's 8R data rate is divided into two 4R parallel rates and codes are assigned to it.

6.4 Zero blocking code assignment scheme

In this design, when *Node B* is ready for the data transmission with i^{th} *UE* represented by UE_i , it generates secondary scrambling code $SC_{s,i}$ and send the same to the UE_i. Now, the user has both the codes of Node $B_{i,}$ namely primary scrambling codes $SC_{p,i}$ (similar to previous scrambling codes) and secondary scrambling code. The *UE* acknowledge the reception of the $SC_{s,i}$. On receiving the acknowledgement, the base station will scramble data using $SC_{s,i}$ instead of $SC_{p,i}$. Hence the base station can utilize the code tree available at the UE_i for the forward link transmission. So the OVSF code tree at the UE_i is shared between UE_i and Node *B*. As each channel in the cell is represented by unique scrambling code $SC_{s,i}$, there is no code blocking. The secondary scrambling code generated at the *Node B* should be unique for each channel in the cell. Also, as each cell has unique primary scrambling code, the secondary scrambling codes generated in a cell need not to be different in different cells. The proposed design requires extra handshaking signals for transmission of $SC_{s,i}$ and acknowledgement reception. In the previous code assignment schemes, the maximum capacity of all the channels is 512R in the downlink. In the proposed design the capacity of the channel is unlimited as far as all the channels use different secondary scrambling codes. The set of operations in forward and reverse direction for the proposed design are given below

Forward Link

1. *Node B* generate secondary scrambling code $SC_{s,i}$ which is having same length as the length of primary scrambling code. It passes $SC_{s,i}$ to the *UE*.
2. In response to the $SC_{s,i}$ signal *UE* send the acknowledgement signal to the *Node B*.
3. On receiving the acknowledgement, *Node B* asks for the OVSF code tree at the *UE*. The code tree at the *Node B* is used only for control signals transmission.
4. The *UE* send the OVSF code tree to the *Node B* (or *Node B* can use the second set of OVSF code tree exactly same as the OVSF code tree available with it).
5. *UE* and *Node B* start data transmission using codes from the same OVSF code tree.

Reverse Link

The set of operations are similar in the reverse link except the fact that in the call initiation, the *UE* requests for the secondary scrambling code.

The proposed design is explained with example shown in Figure 6.7. There are five simultaneous communications in the cell under the control of single *Node B*. The

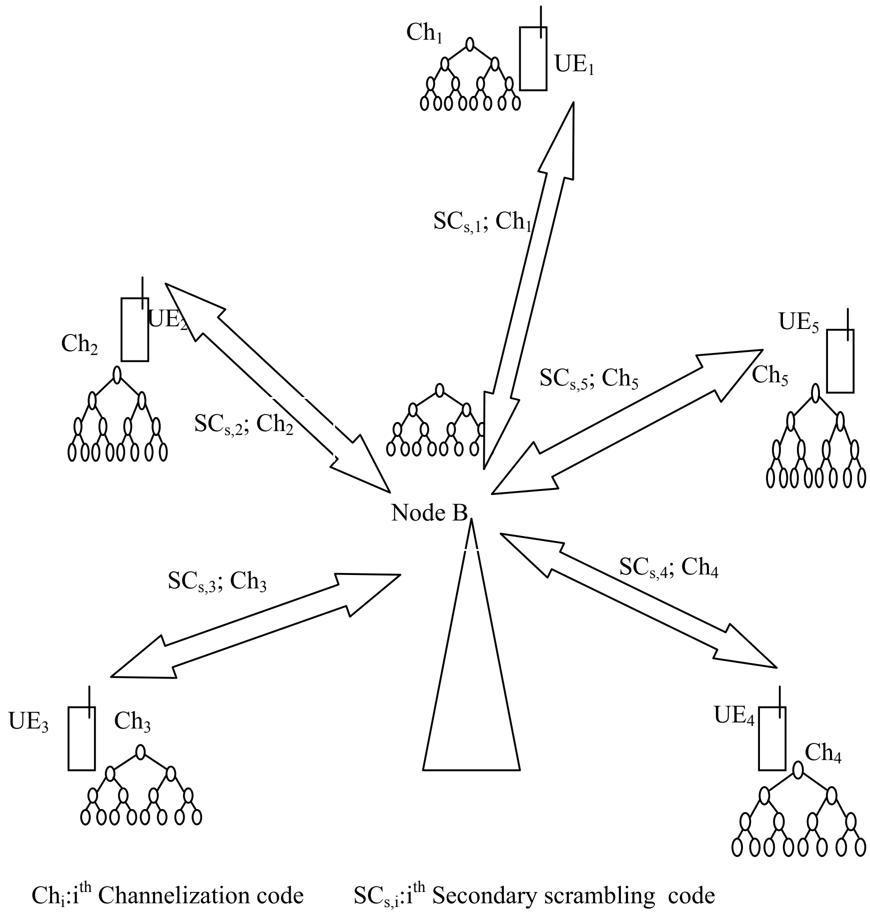


Figure 6.7 Example illustrating five UEs communicating with single Node B. Each channel uses different secondary scrambling code.

data is scrambled using $SC_{s,i}$, $i \in [1,5]$ for channels 1,2,..5 corresponding to UE_i, $i \in [1,5]$. The channelization codes Ch_i, $i \in [1,5]$ may be same or different.

6.5 Single Code Time Multiplexing (SCTM) scheme

6.5.1 Description

We divide the total time frame for code in layer m into 2^{m-1} slots, with code in layer 1 has single slot denoted by T_{ref}. Consider a new call arrival with non-quantized data rate in the form of kR, $k \neq 2^n$, $n \in [2,9]$. Choose minimum m satisfying $k<2^m$. The availability of the code with at least *k* slots is checked in the layer *m*+1. If the vacant slots are available the time frame of the code is divided into two groups of slots T^{1}_{m+1} and T^{2}_{m+1}, where both groups

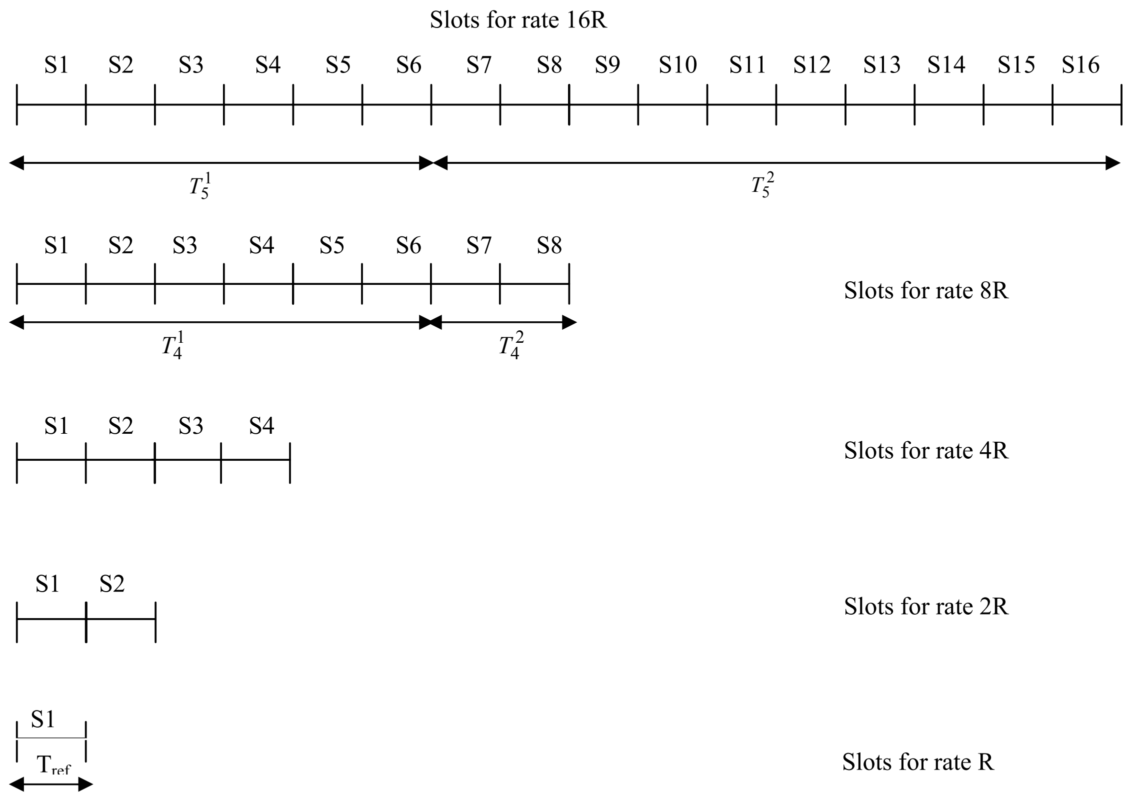


Figure 6.8 Illustration of 6R call handling in single code time multiplexing scheme

are multiple of minimum time slot T_{ref}. The new call is assigned all the slots of T^{1}_{m+1}. The slots in group T^{2}_{m+1} can be utilized by the other calls to come. If the vacant slots are not available, the availability of vacant slots is checked in the layer m+2. If the vacant slots are available, it is once again divided into two groups T^{1}_{m+2} and T^{2}_{m+2}, where $T^{1}_{m+2} = T^{1}_{m+1}/2$. The procedure is repeated up to layer 8 till we get vacant slots.

Optimality Criterion

If multiple options of time slots exist in a layer, the code with the minimum number of vacant slots and greater than the slots required for the new call is chosen. This gives the maximum number of available slots for the new calls to arrive. The procedure is shown in the Figure 6.8 for a five layer system when the new call with rate 6R arrives. The number of slots in the layer 4 and 5 are 8 and 16 respectively. Slot searching is started from layer 4. If vacant slots are available, they are captured by the call otherwise procedure is repeated in layer 5.

6.5.2 Flowchart and Algorithm

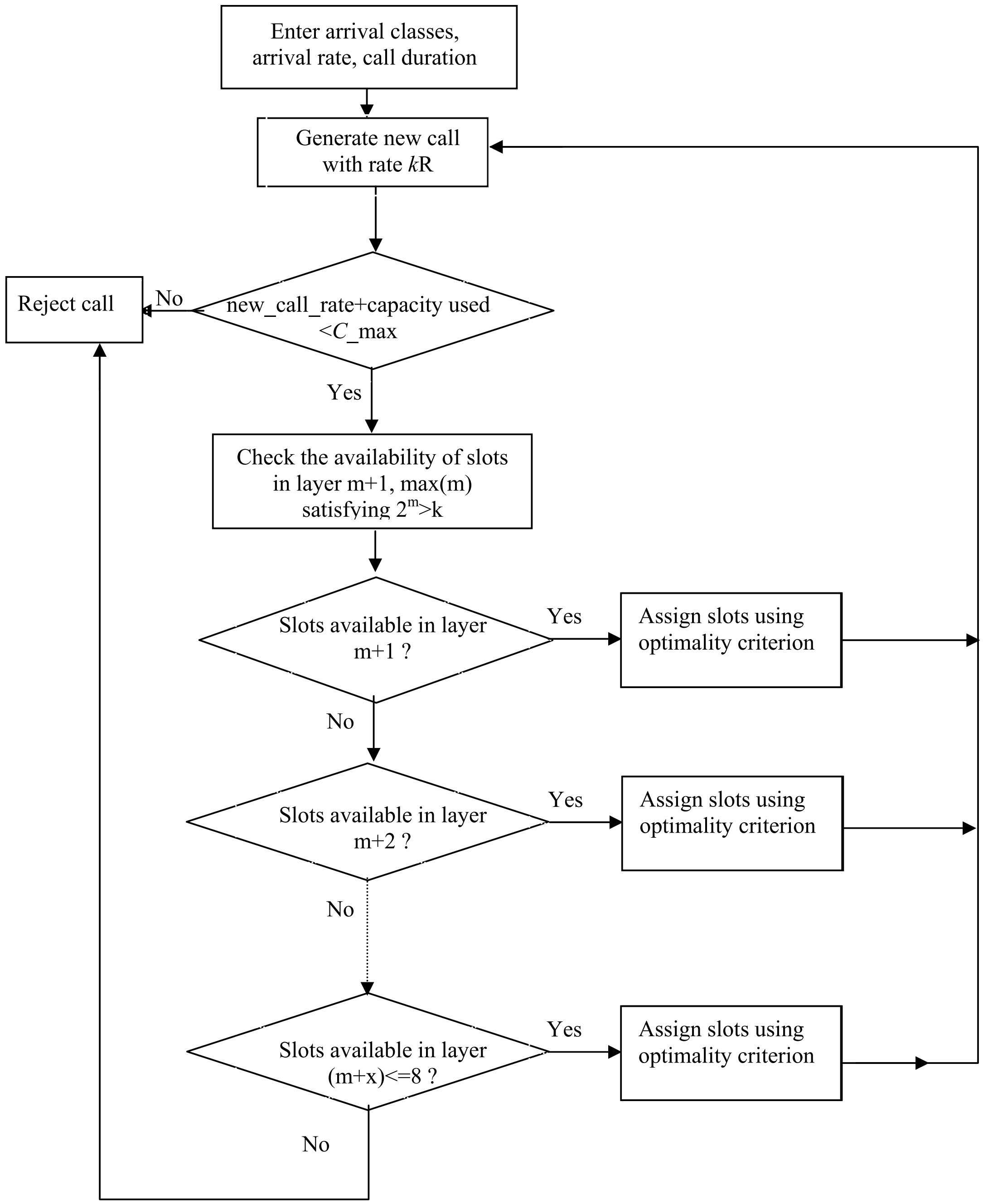


Figure 6.9 Flow chart of single code time multiplexing scheme

The flowchart of single code assignment scheme is given in Figure 6.9. The algorithm is outlined below

1. Input parameters such as arrival rate, call duration and number of layers are entered.

2. Generate new call. For each new call, capacity check is performed to verify that whether new call can be handled by the code tree or not.

3. If the rate of new call is more than the available capacity of the code tree, call is discarded. Otherwise, the vacant slots are searched in the layer m+1 for rate kR, where $2^m > k$ for minimum m.

4. If vacant slots are available, the slots are assigned to the new call according to the optimality criteria discussed. Go to step 2.

5. If the vacant slots are not available in layer m+1, go to layer m+2.The procedure is repeated for vacant slots till layer 8.

6.6 Summary

The chapter proposes code assignment schemes independent of properties of the code tree. The code tree extension increase the capacity of code tree 4 times due to flexibility of codes in layer 8 instead of one code e.g. in present WCDMA system. The bandwidth division scheme allows the lower rate codes to be used for handling higher rate calls, a situation occurs when best effort traffic dominates the call arrival distribution. The zero blocking design is based upon the fact that the OVSF code tree at the UE is under utilized. So the UE code tree is used by the BS for handling calls. The code tree at the BS is not used for traffic transmission but is only used for control signals transmission. The time multiplexing uses single code sharing by multiple users to avoid code blocking.

CHAPTER 7

Conclusion

Wideband CDMA based upon OVSF codes suffer from code blocking. Due to code blocking a new call cannot be handled even the system has enough capacity to handle it. The improper use of OVSF codes decrease the system throughput and code utilization in the OVSF-CDMA system. The thesis proposes a large number of code assignment schemes to overcome code blocking problem. We divide the code assignment schemes into two categories one uses single code and other uses multiple codes for assignment.

7.1 Fast single code assignment schemes

The Adaptive code assignment scheme does the code assignment adaptive to the parameters of the traffic or properties of the code tree. Adaptive code assignment scheme (ADA) does the code assignment adaptive to the distribution of traffic. The code reservation is done in advance from the input traffic distribution. The adaptive tree properties (ATP) scheme does the code assignment adaptive to the tree properties. The code tree properties considered are number of codes and capacity of the tree.

In the fast code assignment (FA)scheme, the code assignment is made most compact such that the codetree having highest density is used for new call if there is enough capacity. If the available capacity is not sufficient, the code tree with second highest density is checked for code availability. The number of codes checked for the new call is least in FA scheme. The number of codes checked is a measure of decision time for finding the suitable vacant code. Therefore the decision time is least in the FA scheme. The reassignments can also be applied and scheme is called fast reassignment (FRA) scheme. The code blocking in the FRA scheme is less than the code assignment in the FA scheme but the decision time may increase in the FRA scheme.

7.2. Code assignment using multiple rake combiners

The multi-code assignment scheme uses multiple codes for handling higher rate non quantized data rates. The use of multiple codes requires same number of rake combiners in the UE. So the hardware complexity in the user part is more compared to all the single code assignment schemes. So a compromise between number of rake combiners (codes in a multi-code) and the complexity need to be specified. The scheme provides performance improvement in non quantized rate dominating scenario. The code blocking is significantly less compared to all the single code assignment schemes.

7.3. Compact single code assignment schemes

In the priority based code assignment scheme the real time calls(voice calls and live video etc.) are treated differently compared to non real time calls (computer data, delay insensitive call etc.). The real time calls are given higher priority. For real time calls, if the vacant code is not available in its corresponding codetree subset, the vacant code is searched in the non real traffic subset. Depending upon the pre decided threshold call may or may not be handled by the code tree.In the compact code assignment (CCA) scheme, the code is assigned to the new incoming call in such a way that the remaining capacity of the system is least fragmented making the assignment scheme most compact. This leads to improved performance of the OVSF-CDMA system. We performed the event-driven simulation to demonstrate the results. Results show that the CCA scheme can outperform the schemes that do not consider the code assignment on the basis of code groups.

The Next Code Precedence High Code Assignment Scheme (NCPH) scheme provides an efficient way to use *OVSF* codes. The code tree is less fragmented due to the compact nature of code assignment scheme. It provides reduction in new call blocking providing higher system throughput and higher code utilization. The *Node* B complexity need to be analyzed due to storage of vacant code precedence numbers.

7.4. Miscellaneous code assignment schemes

The code tree extension extends the code tree four times which increases the number of codes and capacity four times. The extension in the code tree provides drastic improvement in the performance in terms of reduction in the code blocking. The complexity of the system remains same as the number of rake combiner is still one. We also discussed assignment scheme called BDA (Bandwidth division Assignment) to reduce the code blocking and improve system throughput is proposed. The advantage of the BDA scheme is that the code blocking can be made as small as zero because of ability of rate division at the input in small quantized rates. The internal fragmentation can also be made zero because of the rate division. Compared to other single code assignment schemes, BDA scheme requires extra provision at the input to break the higher rate (quantized or non-quantized rate) into smaller rates. In the end, an effort is made to make code blocking zero. The design considers the use of OVSF code tree in the *UE* for the forward link communication. The code/call blocking can be completely eliminated. However, the complexity in the UE needs to be analyzed. Also, the design requires extra overhead (although small) for sending information regarding the secondary channelization codes. The time multiplexing scheme divides the time frame for code usage into slots which can be used for incoming calls. A new code can use all or part of the slots. The vacant slots for same or different codes can be combined to handle higher rate calls. The code blocking can be made zero using the time multiplexing. The slot management becomes the critical issue for the code assignment scheme.

7.5. Scope of future work

For future work, the research can be extended to consider the effects of errors due to wireless nature of transmission. The role of upper layers in the TCP/IP model can be investigated in order to get better results. Also the QoS performance for different type of calls can be investigated. The work in multi-code/multi-rake approach can be explored to reduce the complexity of WCDMA system utilizing multiple rakes. The WCDMA code assignment can be modified to use for other 3G standards like cdma2000.

References

1. H. Holma, A. Toskala. *WCDMA for UMTS. Wiley*, Nokia, Finland, 2000.
2. F.Adachi, M. Sawahashi, and H.Suda. *Wideband CDMA for next generation mobile communication Systems*. IEEE Communication Magazine, vol. 36, pp. 56-69, Sept.1998.
3. K Tachikawa. *W-CDMA Mobile Communication System.* John Wiley and Sons, 2002.
4. Prodip Chaudhury, Werner Mohr, and Seizo Onoe. *The 3GPP Proposal for IMT-2000*. IEEE Communications Magazine, vol. 37, no. 12, pp. 72-81, December 1999.
5. Third generation partnership project. *Technical specification group radio access network, Physical channels and mapping of transport channels onto physical channels (FDD).* GPP TS 25.211V5.3.0, 2002.
6. A. J. Veterbi. *Principles of spread spectrum communications.* Addison Wesley, 1995.
7. R. Kohno, R. Meidan, B. Milstain. *Spread spectrum access method for wireless communications.* IEEE Communication Magazine, pp. 58–67, 1995.
8. R. L. Pickholtz, D. L. Schilling, and L. B. Milstein. *Theory of spread spectrum communications—A tutorial.* IEEE Transactions on Communications, vol. 30, pp. 855–884, May 1982.
9. H. Kaaranen, A. Ahtiainen, L. Laitinen, S. Naghian, V. Niemi. *UMTS Networks – Architecture, Mobility and Services*. John Wiley & Sons, second edition, pp. 406, 2005.
10. *[3GP01i] 3GPP TS 25.213. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network Spreading and Modulation (FDD).* (Release 1999), 2001. Document available at www.3gpp.org
11. E. H. Dinan and B. Jabbari. *Spreading codes for direct sequence CDMA and wideband CDMA cellular networks*. IEEE Communications Magazine, Sep. 1998.
12. *Spreading and Modulation (FDD). 3GPP TS 25.213 (V6.0.0). Technical Specification (Release 6), Technical Specification Group Radio Access Network, 3GPP.* Dec. 2003.

13. *Spreading and Modulation (TDD). 3GPP TS 25.223 (V6.0.0). Technical Specification (Release 6), Technical Specification Group Radio Access Network, 3GPP*. Dec. 2003.
14. Andrew Richardson. *WCDMA Design Handbook.* Cambridge University Press. 2005.
15. R. L. Pickholtz, D. L. Schilling, and L. B. Milstein. *Theory of spread spectrum communications—A tutorial.* IEEE Transactions on Communications, vol. 30, pp. 855–884, May 1982.
16. Roger L. Peterson, Rodger E. Ziemer and David E. Borth. *Introduction to Spread Spectrum Communications.* Prentice Hall, Upper Saddle River, NJ, 1995.
17. Bernard Sklar. *Digital Communications Fundamentals and Applications*. Prentice Hall, New Jersey, 1988.
18. F.Adachi, M.Sawahashi, and K.Okawa. *Tree structured generation of orthogonal spreading codes with different lengths for forward link of DS-CDMA mobile radio.* IEEE Electronic Letters, vol. 33, pp.27-28, Jan. 1997.
19. K. Okawa and F. Adachi. *Orthogonal forward link using orthogonal multi spreading factor codes for coherent DS-CDMA mobile radio*. IEICE Transactions on Communications E81-B(4), pp.778–779, 1998.
20. A.C. Kam, T. Minn, K.Y. Siu. *Reconstruction methods of tree structure of orthogonal spreading codes for DS-CDMA*. IEICE Transactions on Fundamentals E83-A (11), pp. 2078–2084, 2000.
21. C.M.Chao, Y.C.Tseng and L.C.Wang. *Reducing Internal and External Fragmentation of OVSF Codes in WCDMA Systems With Multiple Codes.* IEEE Transactions on Wireless Communication, vol.4., pp. 1516-1526, July 2005.
22. Y.C.Tseng, C.M.Chao, and S.L. *Wu. Code placement and replacement strategies for wideband CDMA OVSF code tree management*. Proceedings of IEEE GLOBECOM, vol. 1, pp.562-566, 2001.
23. A. Rouskas and D. Skoutas. *OVSF code assignment and reassignment at the forward link of W-CDMA 3G systems*. Proceedings of IEEE PIMRC, vol. 5, pp. 2404-2408, 2002.
24. M. Dell'Amico, M. L. Merani, and F. Maffioli. *Efficient algorithms for the assignment of ovsf codes in wideband CDMA*, Proceedings of IEEE International Conference Communications (ICC'02), vol. 5, New York, NY, pp. 3055–3060, 2002.

25. A. Rouskas and D.N. Skoutas. *Comparison of code reservation schemes at the forward link in WCDMA*. Proceedings of 4th IEEE International Conference on Mobile and Wireless Communications Networks 2002, pp. 191–195, Sept. 2002.
26. S. Akhtar, S.A. Malik, D. Zeghlache. *Prioritized admission control for mixed services in UMTS WCDMA networks*. 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, pp. B-133 - B-137, vol.1, 2001.
27. V.K. Garg, O.T.W. Yu. *Integrated QoS support in 3G UMTS networks.* IEEE Wireless Communications and Networking Conference, pp. 1187-1192, vol.3, Sept. 2000.
28. F. Ruijun, S. Junde. *Some QoS issues in 3G wireless networks.* IEEE Control and Power Engineering, pp. 724-727, vol.2, Oct. 2002.
29. Li-Hsing Yen, Ming-Chun Tsou. *An OVSF code assignment scheme utilizing multiple RAKE combiners for W-CDMA*. Elsevier Journal of Computer Communications 27(16), pp. 1617-1623, 2004.
30. L. H. Yen and M. C. Tsou. *An OVSF code assignment scheme utilizing multiple rake combiners for W-CDMA*. Proceedings of IEEE International Conference Communications (ICC'03), vol. 5, Anchorage, AK, pp. 3312–3316, May 2003.
31. T.Minn and Kai-Yeung Siu. *Dynamic Assignment of orthogonal variable spreading factor codes in W-CDMA.* IEEE J. Selected Areas in Communication, vol. 18, no.8, pp. 1429-1440, Aug. 1998.
32. C. E. Fossa, Jr. and N. J. Davis, IV. *Dynamic code assignment improves channel utilization for bursty traffic in third-generation wireless networks*. Proceedings of IEEE International Conference Communications (ICC'02), vol. 5, New York, pp. 3061–3065, 2002.
33. J. S. Kaufman. *Blocking in a shared resource environment.* IEEE Trans Communication, vol. COM-29, no. 10, pp. 1474–1481, Oct. 1981.
34. M. Zafer and E. Modiano. *Blocking Probability and Channel Assignment in Wireless Networks*. IEEE Transactions on Wireless Communications, vol. 5, no. 4, April 2006.
35. M. Kemal Karakayali, Roy D. Yates, and L V. Razoumov. *Downlink Throughput Maximization in CDMA Wireless Networks.* IEEE Transactions on Wireless Communications, vol. 5, no. 12, Dec. 2006.

36. S. Malik and D. Zeghlache. *Improving Throughput and Fairness on the downlink Shared Channel in UMTS WCDMA Networks.* European Wireless 2002, Florence, Italy, Feb. 2002.
37. H. Qam and N. Challa. *Supporting rate and soft delay guarantees for data traffic in the downlink shared channel of WCDMA*. Proceedings of International Conference on Wireless Networks (ICWN) 2002, Las Vegas, USA, June 2002.
38. A.C. Kam, T. Minn, K.Y. Siu. *Supporting rate guarantee and fair access for bursty data traffic in WCDMA*. IEEE Journal on Selected Areas in Communications 19 (11) (2001), pp. 2121–2130. Nov. 2001.
39. Liang Xu, Xuemin Shen, and Jon W.Mark. *Dynamic Bandwidth Allocation with fair scheduling for WCDMA systems*. IEEE Wireless Communications, pp. 26-32, April 2002.
40. Fenfen Shueh, Zu-En Liu, and Wen-Shyen Chen. *A fair, efficient, and exchangeable channelization code assignment scheme for IMT-2000.* Proceedings of 2000 IEEE International Conference on Personal Wireless Communications, pp. 429–433, 2000.
41. Erik Dahlman, Bjorn Gudmunson, Mats Nilsson, and Johan Skold. *UMTS/IMT-2000 Based on Wideband CDMA*. IEEE Communications Magazine, vol. 36, no. 9, pp. 70.80, Sept. 1998.
42. Tero Ojanperä and Ramjee Prasad. *An Overview of Air Interface Multiple Access for IMT-2000/UMTS*. IEEE Communications Magazine, vol. 36, no. 9, pp. 82.95, Sept. 1998.
43. *Radio Interface Protocol Architecture*. 3rd Generation Technical Specification 25.301 (Release 1999).
44. H. Holma, F. Ovesj¨o, E. Dahlman, M. Latva-aho, and A. Toskala. *Physical layer of FRAMES mode 2—Wideband CDMA*. Proceedings of 48th IEEE Veh. Technol. Conf., VTC'98, Ottawa, Canada, pp. 978–982, May 1998.
45. Chih-Min Chao; Yu-Chee Tseng; Li-Chun Wang. *Reducing internal and external fragmentations of OVSF codes in WCDMA systems with multiple codes.* Proceedings of IEEE WCNC 2003 Vol. 1, pp.:693 - 698 vol.1, March 2003.
46. Huei-Wen Ferng, Hao-Lun Chin, David Shiung, and Ying-Tsung Chen. *An OVSF Code Tree Partition Policy for WCDMA Systems Based on the Multi-Code Approach*. Proceedings of VTC 2005, Vol. 2, pp.1212 – 1216, 25-28 Sept. 2005.

47. M. Dell'Amico, M. L. Merani, and F. Maffioli.*Efficient Algorithms for the Assignment of OVSF Codes in Wideband CDMA*. Proceedings of IEEE ICC02, Vol. 5, pp.:3055 - 3060 vol.5, 28 April-2 May 2002.
48. J. S. Park and D. C. Lee. *On static and dynamic code assignment policies in the OVSF code tree for CDMA networks.* Proceedings of IEEE Military Communications Conference (MILCOM'02), vol. 2, Anaheim, CA, pp. 785–789, Oct. 2002.
49. J.S.Park and D.C.Lee. *Enhanced fixed and dynamic code assignment policies for OVSF-CDMA systems.* Proceedings of ICWN 2003, Las Vegas, June 2003.
50. T. Minn and Kai-Yeung Siu. *Dynamic Assignment of orthogonal variable spreading factor codes in W-CDMA.* IEEE J. Selected Areas in Communication, vol. 18, no.8, pp. 1429-1440, Aug. 1998.
51. Chih-Min Chao, Yu-Chee Tseng, Li-Chun Wang. *Dynamic Bandwidth Allocation for Multimedia Traffic with Rate Guarantee and Fair Access in WCDMA Systems.* IEEE Transactions on Mobile Computing, Vol.4, No.5, pp.420-429, Sep./Oct. 2005.
52. Liang Xu, Xuemin Shen, and Jon W.Mark. *Dynamic Bandwidth Allocation with fair scheduling for WCDMA systems.* IEEE Wireless Communications, pp. 26-32, April 2002.
53. C. E. Fossa, Jr. and N. J. Davis. *Dynamic code assignment improves channel utilization for bursty traffic in third-generation wireless networks.* Proceedings of IEEE International Conference Communications (ICC'02), vol. 5, pp. 3061–3065, New York, 2002.
54. Skoutas, D.N. Rouskas, A.N. *A Dynamic Traffic Scheduling Algorithm for the Downlink Shared Channel in 3G WCDMA.* Proceedings of International Conference on Communications, pp.2975- 2979, Vol.5, 2004.
55. Erik Dahlman and Karim Jamal. *Wide-band services in a DS-CDMA based FPLMTS system.* Proceedings of IEEE Vehicular Technology Conference 1996, pp. 1656-1660, vol.3, 1996.
56. B.-J. Chang and P.-S. Chang. *Multicode-based WCDMA for reducing waste rate and reassignments in mobile cellular communications.* Computer Communication, vol.29, no.11, pp.1948–1958, July 2006.

57. Ferng, H.-W. Hao-Lun Chin Shiung, D. Ying-Tsung Chen. *An OVSF Code Tree Partition Policy for WCDMA Systems Based on the Multi-Code Approach.* Proceedings of IEEE VTC-Fall, vol.2, pp. 1212-1216, 2005.
58. Cruz-Perez, F.A. Vazquez-Avila, J.L. Seguin-Jimenez, A. Ortigoza-Guerrero, L. *Call Admission and Code Allocation Strategies for WCDMA Systems With Multirate Traffic.* IEEE Journal on Selected Areas in Communications pp.26-35, vol.24, Jan. 2006.
59. Y. Sekine, K. Kawanishi, U. Yamamoto, and Y. Onozato. *Hybrid OVSF code assignment scheme in W-CDMA.* Proceedings of IEEE Pacific Rim Conference Communications, Computers and Signal Processing (PACRIM'03), vol. 1, Victoria, BC, Canada, pp. 384–387, Aug. 2003.
60. Y.-C. Tseng and C.-M. Chao. *Code placement and replacement strategies for wideband CDMA OVSF code tree management.* IEEE Transactions on Mobile Computing 1(4), pp. 293–302, 2002.
61. R. Assarut, K. Kawanishi, U. Yamamoto, Y. Onozato, and M. Matsushita. *Region division assignment of orthogonal variable spreading-factor codes in W-CDMA.* Proceedings of IEEE Vehicular Technology Conference, 2001, vol. 3, Atlantic City, NJ, pp. 1884–1888, Fall 2001.
62. Rujipun Assarut, Ken'ichi Kawanishi, Ushio Yamamoto and Yoshikuni Onozato. *Region Division Assignment: A New OVSF Code Reservation and Assignment Scheme for Downlink Capacity in W-CDMA Systems.* Wireless Networks 12(3), pp.357-368, 2006.
63. Angelos N. Rouskas, and Dimitrios N. Skoutas. *Management of Channelization Codes at the Forward Link of WCDMA.* IEEE Communications Letters, Vol. 9, No. 8, August 2005.
64. A. Rouskas and D. Skoutas. *OVSF code assignment and reassignment at the forward link of W-CDMA 3G systems*. Proceedings of IEEE PIMRC, vol. 5, pp. 2404-2408, 2002.
65. Yuh-Shyan Chen, Ting-Lung Lin. *Code Placement and Replacement Schemes for WCDMA Rotated-OVSF Code Tree Management*. IEEE Transactions on Mobile Computing, vol. 05, no. 3, pp. 224-239, Mar., 2006
66. Yuh-Shyan Chen; Han-Chen Chang. *Multi-code placement and replacement schemes for W-CDMA rotated-OVSF code tree.* IEEE 6th Circuits and Systems Symposium Vol. 1, pp.:345 - 348 Vol.1, 2004.

67. Hasan Çam. *Nonblocking OVSF Codes for 3G Wireless and Beyond Systems.* Proceedings of 3Gwireless'2002 & WAS'2002. 2002 International Conference on Third Generation Wireless and Beyond, May 28-31, San Francisco, CA, USA, pp. 148-153, 2002.
68. Hasan Çam. Nonblocking *OVSF Codes and Enhancing Network Capacity for 3G Wireless and Beyond Systems.* Special Issue of Computer Communications on ``3G Wireless and Beyond for Computer Communications'', vol.26, no. 17, pp. 1907-1917, Nov. 2003.
69. H.Qam. *Non-blocking OVSF codes and enhancing network capacity for 3G wireless and beyond systems.* Elsevier Journal, Computer Communication, pp. 1907-1917, 2003.
70. H. C¸ am, K. Vadde. *Performance analysis of nonblocking OVSF codes in WCDMA,* Proceedings of the 2002 International Conference on Wireless Networks, June 24–27, Las Vegas, USA, 2002.
71. Kiran Vadde and Hasan Çam. *A code assignment algorithm for Non blocking OVSF codes in WCDMA*. Special Issue of Telecommunication Systems on Recent Advances in Communication and Internet Technology, vol. 25, no. 3 and 4, pp. 417-431, March/April 2004.
72. Karakayali, M.K.; Yates, R.D.; Razoumov, L.V. *Downlink Throughput Maximization in CDMA Wireless Networks.* IEEE Transactions on Wireless Communications, Vol. 5, issue 12, pp. 3492 – 3500, Dec. 2006.
73. Sheng-Tzong Cheng and Ming-Tzung Hsieh. *Design and Analysis of Time-Based Code Allocation Schemes in W-CDMA Systems.* IEEE Transactions on Mobile Computing, Vol. 4, No. 6, 604-615, Nov./Dec. 2005.
74. Yih-Fuh Wang, Hsing-Hu Chen,Tun-Ying Lin. *New Non-blocking EOVSF Codes for Multi-Rate WCDMA System.* Proceedings of IWCMC'06, 839-844, July 3–6, 2006.
75. Yang Yang and Tak-Shing Peter Yum. *Multicode Multirate Compact Assignment of OVSF Codes for QoS Differentiated Terminals.* IEEE Transactions on Vehicular Technology, Vol. 54, No. 6, pp. 2114-2124, Nov. 2005.
76. Y. Yang and T.-S. P. Yum. *Maximally flexible assignment of orthogonal variable spreading factor codes for multirate traffic*. IEEE Transactions on Wireless Communication, vol. 3, no. 3, pp. 781–792, May 2004.

77. J.-S. Park, L. Huang, D. C. Lee, and C.-C. Jay Kuo. *Optimal code assignment and call admission control for OVSF-CDMA systems constrained by blocking probabilities.* IEEE Globecom 2004, Dallas, Dec. 2004.
78. Y. Yang and T.-S. P. Yum. *Nonrearrangeable compact assignment of orthogonal variable-spreading-factor codes for multi-rate traffic.* IEEE Vehicular Technology Conference (VTC), Atlantic City, NJ, vol. 2, pp. 938–942, 2001.
79. A. Rouskas and D. Skoutas. *OVSF code assignment and reassignment at the forward link of W-CDMA 3G systems.* Proceedings of IEEE PIMRC, vol. 5, pp. 2404-2408, 2002.
80. Wen-Tsuen Chen, Hung-Chang Hsiao, and Ya-Ping Wu. *A novel code assignment scheme for W-CDMA systems.* Proceedings of IEEE Vehicular Technology conference, vol. 2, pp.1182-1186, 2001.
81. H. Gharavi and S. M. Alamouti. *Video Transmission for Third Generation Wireless Communication Systems.* Vol. 106, Number 2, 455-469, March–April 2001.
82. Jun Xu, Xeumin (Sherman) Shen, Jon W. Mark, Jun Cai. *Efficient Channel Utilization for Real-Time Video in OVSF-CDMA Systems with QoS Assurance.* IEEE Transactions on Wireless Communications, pp. 1382-1391,Vol. 5, No. 6, June 2006.
83. Jun Xu, Xeumin (Sherman) Shen, Jon W. Mark, Jun Cai. *Efficient Real-time Video Transmission in OVSF-CDMA System*. Proceedings of IEEE WCNC, pp. 1329-1335, 2005.

Author's Publications

- D.S.Saini and S.V.Bhooshan. *Code reservation and reduction in multimedia call blocking for OVSF-WCDMA*. To be published in proceedings of IEEE Indicon 2007, Bangalore, India, Sept 2007.
- D.S.Saini and S.V.Bhooshan. *An optimum algorithm to minimize the number of rake combiners in WCDMA*. To be published in proceedings of IEEE Indicon 2007, Bangalore, India, Sept 2007.
- D.S.Saini and S.V.Bhooshan. *Handling Non-quantized data rates in 3G and beyond Wideband CDMA systems based on OVSF codes.* Proceedings of international conference on wireless and mobile communication, IEEE *ICWMC07*, French Caribbean, April 2007.
- D.S.Saini and S.V.Bhooshan. *Multiple rake combiners and performance improvement in WCDMA systems.* Proceedings of IEEE WCNC 2007, Hong Kong, March 2007.
- D.S.Saini and S.V.Bhooshan. *Code Tree Extension and Performance improvement in OVSF-CDMA Systems*. Proceedings of IEEE-ICSCN07, pp. 316-319, Chennai, Feb.2007.
- D.S.Saini and S.V.Bhooshan. *Performance Improvement in 3G and beyond CDMA Systems using Priority Based Code Assignment Scheme.* Proceedings of IEEE-ICSCN07, pp. 98-102, Chennai, Feb.2007.
- D.S.Saini, S.V.Bhooshan and T. Chakravarty. *OVSF code groups and reduction in call blocking in WCDMA system*. GESTS International Transactions on Communication and Signal Processing, Korea, Vol.09, No.01, October 30, 2006.
- D.S.Saini and S.V.Bhooshan. *Fast Code Assignment Schemes for Third Generation and Beyond CDMA Wireless Communication Systems*. Int'l Journal HIT Transactions on ECCN, India, ISSN 0973-6875, vol.1. No.2. pp 118-127, June 2006.
- D.S.Saini and S.V.Bhooshan. *Adaptive assignment scheme for OVSF codes in WCDMA*. Proceedings of IEEE *ICWMC06*, Bucharest, July29-31, 2006.
- D.S.Saini and S.V.Bhooshan. *Assignment and Reassignment Schemes for OVSF Codes in WCDMA*. Proceedings of ACM *IWCMC2006*, Vancouver, pp. 497-501, July 3-6, 2006.
- D.S.Saini and S.V.Bhooshan. *An efficient code reassignment scheme in OVSF-WCDMA*. Abstract in *NCCCB06*, national conference on communication and control, pp.29, ECK Kota Rajasthan, India, March 9, 2006.
- D.S.Saini and S.V.Bhooshan. *A novel assignment scheme to reduce code searches in OVSF-CDMA.* Proceedings *ECCS-06*, national conference on communication, pp. 379-383, TIET Patiala, India. Feb.9, 2006.

Papers Communicated

- D.S.Saini and S.V.Bhooshan. *Design of zero blocking 3G and beyond WCDMA system based on OVSF codes,* AEUE Elsevier communication letters.
- D.S.Saini and S.V.Bhooshan. *OVSF Code Sharing and Reducing the Code Wastage Capacity in WCDMA***.** Springer Wireless Personal Communication letters.
- D.S.Saini and S.V.Bhooshan. *Multiple rake combiners and performance improvement in WCDMA systems.* IEEE Transactions on Wireless Communications.

- D.S.Saini and S.V.Bhooshan *Adaptive Assignment and Reassignment Schemes for OVSF Codes in Wideband CDMA*. Springer Journal of Wireless Personal Communication.
- D.S.Saini and S.V.Bhooshan *Throughput maximization in 3G and beyond CDMA wireless communication systems*. Communicated to IEEE ICSCN 2008, Chennai, INDIA.
- D.S.Saini and S.V.Bhooshan. *OVSF Code Assignment schemes at the forward link of WCDMA Systems.* Actapress journal of Wireless Communication.
- D.S.Saini and S.V.Bhooshan. *OVSF Code Sharing and Reducing the Code Wastage Capacity in WCDMA***.** IEEE transactions on mobile computing.