Mobile Networks

A hybrid multirate MAC protocol providing trade-off between throughput and fairness in future TD-CDMA networks


School of Electrical and Computer Engineering, National Technical University of Athens, 9 Heroon Polytechniou Street, Zographou, 15773, Athens, Greece

SUMMARY

In this paper, a hybrid, frequency division duplex (FDD), time division–code division multiple access (TD-CDMA), medium access control (MAC) protocol is proposed. Both multicode (MC) and orthogonal variable spreading factor (OVSF) transmission modes are used in order to utilise the system resources more efficiently. Moreover, a new rate-scheduling algorithm is developed, aimed at providing a trade-off between throughput maximisation and fairness, while satisfying QoS requirements. The above scheme is formulated as a constrained optimisation problem, which maximises the sum of normalised rates instead of throughput in order to achieve fairer rate allocations, while maintaining throughput at a high value. A new optimisation constraint is introduced in order to deal with the discrete set of available rates that the hybrid MC-OVSF scheme supports. Copyright © 2009 John Wiley & Sons, Ltd.

1. INTRODUCTION

As the wireless world is moving towards heterogeneous networks, wideband code division multiple access (WCDMA) and time division–code division multiple access (TD-CDMA) are among the access technologies [1, 2], which will be connected using Mobile IP in order to provide seamless communication for mobile users. These wireless networks require efficient medium access control (MAC) protocols to manage packet access.

However, few MAC protocols for future Internet Protocol (IP)-based TD-CDMA networks have been proposed. A MC TD-CDMA system is presented in Reference [1]. Due to hardware complexity, the limited number of substreams results in a great degradation of throughput taking into account that each substream uses the basic transmission rate. In Reference [2] a minimum-power allocation scheme, which considers both multicode (MC) and orthogonal variable spreading factor (OVSF) operations for pure WCDMA systems, is proposed. However, the analysis does not try to optimise the resource utilisation. Moreover, it is based on code level, not allowing the mobile terminal (MT) to select itself which codes to use after rate allocation. Therefore, the base station (BS) is in charge of this selection, which complicates its operation since it has to compute and send back to each MT the spreading gain and the power level per code channel.

QoS provisioning and efficient utilisation of the limited radio resources remain key targets of all future integrated networks. This task is more complex in CDMA based systems as the capacity is interference-limited and power is considered as a kind of resource along with bandwidth. In Reference [3] a power control and resource management system for multimedia CDMA is presented. Both total transmitted power minimisation and throughput maximisation are investigated as optimisation criteria.

*Correspondence to: Panagiotis T. Vlacheas, School of Electrical and Computer Engineering, National Technical University of Athens, 9 Heroon Polytechniou Street, Zographou, 15773, Athens, Greece. E-mail: panvlah@telecom.ntua.gr

Received 3 November 2008
Revised 15 May 2009
Accepted 20 October 2009

Copyright © 2009 John Wiley & Sons, Ltd.
However, if a high transmission rate is allocated to a user, a high transmission power is required, leading to more interference to other users which forces them to starve from resources. On the other hand, a lower rate allows more users to transmit but prolongs the interference duration and often results in under-utilisation of system resources.

The present work proposes a hybrid multirate MAC protocol, which considers both MC and OVSF operations. The analysis focuses on the whole terminal and not on each code separately. The resource allocation (RA) is formulated as an optimisation problem subject to a set of QoS constraints. A novel algorithm, which enables us to efficiently trade off between throughput and fairness, is presented. Moreover, we introduce a new optimisation constraint in order to be consistent with the discrete set of rates that our hybrid scheme supports. Although we work on TD-CDMA, the same algorithm can be applied to pure WCDMA.

2. SYSTEM MODEL AND ANALYSIS

In this paper, we consider a cellular frequency division duplex (FDD) TD-CDMA system, which is connected to the core network via a BS. The BS is both the edge router of the core network and the responsible module for the RA, which is then transmitted to the MTs. We focus on the link layer, in order to analyse our hybrid multirate MAC protocol. Moreover, we present only the uplink, which is more complicated than downlink due to interference and power limitations of the MTs. Time is divided in fixed-length frames. Each uplink frame consists of one request slot and a fixed number of transmission slots. The MTs use the request slot to send request and control packets, while the other slots are channels dedicated to packet transmission.

Let \( N \) be the total number of MTs in a system cell. For simplicity, we suppose that each MT runs one service each time. Each terminal \( n (n \in \{1, \ldots, N\}) \) is characterised by its minimum requirements \( \gamma_n \) in \( E_b/N_0 \), in order to satisfy the service bit error rate (BER). In our hybrid MC-OVSF scheme, a set of orthogonal codes \( C_n = [C_{1,n}, \ldots, C_{M,n}] \) with variable spreading gains is assigned to the terminal \( n \). These codes are derived by an OVSF tree with \( M \) levels. \( C_{m,n} \) denotes the number of \( m \)-level codes \( (m \in \{1, \ldots, M\}) \), which are used by the terminal \( n \). The transmission rate of an \( m \)-level code is \( R_m = W/G_m \), where \( G_m = 2^{m-1} \) is the spreading gain of the \( m \) level and \( W \) the system bandwidth. The total number of codes in vector \( C_n \) is generally limited. The first reason is that, due to orthogonality, no code should lie on the path from another code to the OVSF tree root. The second reason is that there is an upper bound \( U \) on this overall number because of the hardware complexity that the transceiver units introduce to the MT.

In order to simplify the analysis, received power at the BS (instead of power transmitted by MT) is considered in this paper. Either a closed-loop or an open-loop power control algorithm [4] can be used to derive the transmitted power level from the received power level and the estimated channel gain. Let \( S_{m,n} \) denote the received power of an \( m \)-level code used by the terminal \( n \), \( S_n = [S_{1,n}, \ldots, S_{M,n}] \) the received power vector of \( C_n \), and \( S_{\text{max},n} \) the upper limit of the overall received power per terminal \( n \).

The next step is to solve the minimum-power allocation problem for our hybrid scheme. The result will be used later as an initial condition in the constrained optimisation problem which trades off between throughput maximisation and fairness. Our analysis focuses on the whole terminal and not on each code separately. We define the overall received power \( S_{\text{sum},n} \) and the overall transmission rate \( R_n \) of terminal \( n \) as

\[
S_{\text{sum},n} = \sum_{m=1}^{M} C_{m,n} S_{m,n}
\]

\[
R_n = \sum_{m=1}^{M} \frac{C_{m,n} W}{G_m}
\]

Considering a transmission slot, the ratio \( E_b/N_0 \) of a specific \( m \)-level code of terminal \( n \) must satisfy

\[
\frac{E_b}{N_0}_{m,n} = \frac{G_m S_{m,n}}{\sum_{\substack{j=1 \atop j \neq n}}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W} \geq \gamma_n
\]

given that

\[
0 < S_{\text{sum},n} \leq S_{\text{max},n} \quad \forall n \in \{1, \ldots, N\}
\]

where \( I_{\text{inter}} \) is the intercell interference and \( N_0 \) the noise spectral density. There is no interference among the codes of the same terminal due to the orthogonality and the same transmission environment.

The minimum-power allocation approach implies that the equality in Equation (3) must hold true. Solving this
equation for $S_{m,n}$ yields

$$S_{m,n} = \frac{\gamma_n}{G_m} \left( \sum_{j=1}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W \right)$$  \hspace{1cm} (5)$$

where $m \in \{1, \ldots, M\}$, $n \in \{1, \ldots, N\}$. According to Equation (5), we note that two $m$-level codes of terminal $n$ have the same power level $S_{m,n}$, since they satisfy the same $\gamma_n$, they have equal spreading gains $G_m$ and they experience the same interference from other terminals.

Combining Equations (1), (2), (4) and (5) and after the analysis found in the Appendix, we conclude that the allocation of the $N$ terminals is feasible in a time slot, in terms of rates, $E_b/N_0$ requirements and power constraints, only when

$$\sum_{j=1}^{N} \left( \frac{W}{\gamma_j R_j} \right) + 1 \leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\sum_{j=1}^{N} \left( \frac{W}{\gamma_j R_j} \right) + 1 \leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

$$\leq 1 - \max_{n=1,\ldots,N} \frac{I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \left( \frac{W}{\gamma_n R_n} \right) + 1$$

For the rest of the paper, we call the second part of Equation (6) normalised system capacity and

$$F_n = \frac{1}{\left( \frac{W}{\gamma_n R_n} \right) + 1}$$  \hspace{1cm} (7)$$

normalised rate of terminal $n$.

The overall received power $S_{\text{sum},n}$ of terminal $n$ can be computed by

$$\left( \frac{W}{\gamma_n R_n} + 1 \right) \left( 1 - \sum_{j=1, j\neq n}^{N} \left( \frac{1}{\left( \frac{W}{\gamma_j R_j} \right) + 1} \right) S_{\text{sum},n} \right)$$

$$= I_{\text{inter}} + N_0 W$$ \hspace{1cm} (8)$$

The overall transmission rate $R_n$ of terminal $n$ is given in terms of powers by

$$R_n = \frac{W}{\gamma_n} \frac{S_{\text{sum},n}}{\sum_{j=1, j\neq n}^{N} \left( \frac{S_{\text{sum},j} + I_{\text{inter}} + N_0 W}{S_{\text{sum},n}} \right)}$$ \hspace{1cm} (9)$$

The proof of Equations (8) and (9) can be found in the Appendix.

We note that the Equations (1), (2) and the inequality (4) must hold in order that the condition (6) and the Equations (8) and (9) are valid for our hybrid scheme. The rate $R_n$ in Equation (9) is not a continuous variable (as in Reference [3]), but belongs to a discrete set according to Equation (2). The set of available rates can be determined based on the following equation [5]:

$$f^U(i) = \begin{cases} 2^\lfloor \log_2 i \rfloor R_b & U = 1 \\ 2^\lfloor \log_2 i \rfloor R_b + f^{U-1}(i - 2^\lfloor \log_2 i \rfloor) R_b & U \geq 2, U \geq N(i) \end{cases}$$ \hspace{1cm} (10)$$

The function $f^U(i)$ gives the minimal rate (the closest upper approximation), which can be assigned to a request for a rate $R_n$, based on the basic transmission rate $R_b$ of the OVSF tree (rate of the $M$-level code) and the upper bound $U$ on the total number of codes, which can be used simultaneously by the terminal. The parameter $i$ is the result of the division of rate $R_n$ by $R_b$ and $N(i)$ is the number of ones in the binary representation of $i$ (e.g. $N(5) = N(101_2) = 2$).

3. RATE SCHEDULING

Before formulating the optimisation problem, it would be useful to investigate how the requests from the MTs are processed by the BS. The scheduler is shown in Figure 1.

We consider two types of services, namely real-time (RT) and non real-time (NRT). The RT service aims at providing a low-delay, low-loss and low-jitter connection (VoIP, videoconference) and uses User Datagram Protocol (UDP) at the transport layer. UDP packets are generated periodically depending on the encoding rate and the UDP packet size. The NRT service intends to establish a reliable connection with a minimum guaranteed rate (computer data, email). TCP is used for NRT applications, providing reliability due to retransmissions. The IP layer is considered to be transparent, generating a fixed amount of overhead. In our hybrid multirate scheme, a variable-length packet is generated. This packet is then segmented into a variable number of fixed-length MAC packets, the size of which is given by $L = R_b t_s$, where $R_b$ is the basic transmission rate of the OVSF tree and $t_s$ the slot duration.

The scheduler must first guarantee the transmission of the delay-sensitive RT packets, while the NRT connections will share the remaining resources. In order to achieve this,
the requests are classified and backlogged in two separate priority queues [6]: guaranteed queue for RT applications and best effort queue for NRT applications. The RA is first applied on the guaranteed queue, while the best effort queue is served as long as resources are available. Existing algorithms (e.g. FIFO, Round Robin) may be used for the classification inside each queue. Moreover, an additional policy, which would give priority to the already established RT connections against new ones, could be applied in order to guarantee a low dropping probability.

Two different RA schemes are defined, namely DRA (demanding) and ARA (available). DRA algorithm is applied on the guaranteed queue and ensures that the requested resources are allocated to the terminals with RT applications. If the capacity is not enough, the remaining RT connections will be served in the next slot. Regarding the NRT connections, there is not a strict rate requirement but a minimum guaranteed rate. If the resource controller assumed the minimum rate, a large number of NRT connections would be allowed to transmit, which would lead to higher interference and throughput degradation. Thus, the resource controller needs a different criterion in order to specify the acceptable number of these connections. An upper bound is considered on the number of NRT connections which will transmit in the slot. This bound is adjusted dynamically in each slot depending on the remaining resources and is called transmission window (w).

In our scheme, we try to keep w as low as possible, so that the interference is reduced and the throughput remains high. In order to achieve this, the resource controller (which is based on Equation (6)) assumes that NRT connections transmit at peak rate. The peak rate is the minimum value between the maximum rate $R_{\text{max}}$ of the OVSF tree and the residual message size $R_{\text{res},n}$ of terminal $n$ in units of rate. Finally, if there are still remaining resources, an additional NRT connection is allowed to transmit, i.e. $w$ increases by one.

After determining how many and which terminals transmit, the next step is to allocate the resources among them. In this paper, we propose a novel approach concerning the optimisation of the RA, in order to trade off between throughput and fairness. We try to maximise the sum of normalised rates instead of throughput. The throughput maximisation guides to solutions, where the MTs either transmit at maximum rate (or power) or do not transmit [7]. This ‘bang-bang’ strategy leads to unfair rate allocations, where some MTs may starve from resources. On the other hand, our approach ensures that the rates of the MTs are close enough and the total throughput remains at a high value. According to Equation (7), the normalised rate of a terminal increases when the corresponding transmission rate becomes higher. So, high rates are required in order to maximise the sum of normalised rates. However, this sum is upper-bounded by the normalised capacity (second part of Equation (6)). The normalised capacity is determined by the terminal with the maximum rate. When this maximum rate has a value close to the peak rate, the normalised capacity
is reduced. On the other hand, the normalised capacity and subsequently the sum of normalised rates are maximised when this maximum rate is reduced. The decrease of the maximum rate leads to more capacity available for the other terminals and improves the fairness.

Let \( N \) denote in this section the number of terminals to transmit in the specific time slot, which has been determined by the resource controller. \( N_1 \) of them run RT applications and DRA algorithm allocates the requested rate \( r_n \) to each terminal \( n \) (\( n \in \{1, \ldots, N_1\} \)). The rest of the terminals, the number of which is equal to the transmission window \( (w = N - N_1) \), run NRT applications and ARA algorithm guarantees a minimum acceptable rate \( R_{\min,n} \) per terminal \( n \) (\( n \in \{N_1 + 1, \ldots, N\} \)). The maximum rate, which ARA algorithm is able to allocate to these terminals, should not exceed the minimum between the maximum rate \( R_{\max} \) of the OVSF tree and the residual message size \( R_{\text{res},n} \) of terminal \( n \) in units of rate.

The optimisation problem is then formulated to find the power vector \( S_{\text{sum}} = [S_{\text{sum},1}, \ldots, S_{\text{sum},N}] \) in order to:

\[
\text{Maximise } \sum_{n=1}^{N} F_n \tag{11}
\]

Substituting the definition of normalised rate \( F_n \) (7) and the equation of rate \( R_n \) (9) into Equation (11) yields

\[
\text{Maximise } \frac{\sum_{n=1}^{N} S_{\text{sum},n}}{\sum_{n=1}^{N} S_{\text{sum},n} + I_{\text{inter}} + N_0 W} \tag{12}
\]

subject to the power constraints (4) and the following additional constraints

\[
R_n = r_n \quad n = 1, \ldots, N_1 \tag{13}
\]

\[
R_{\min,n} \leq R_n \leq \min(R_{\max}, R_{\text{res},n}) \quad n = N_1 + 1, \ldots, N \tag{14}
\]

\[
\sum_{n=1}^{N} R_n \geq aT \tag{15}
\]

where \( R_n \) is given by Equation (9). The constraints (13) and (14) refer to RT and NRT connections, respectively.

The constraint (15) guarantees that the total throughput exceeds a threshold. The parameter \( T \) denotes the maximum throughput. \( T \) can be derived by the resource controller when we determine the transmission window \( w \), since we have assumed that NRT connections use the peak rate. The last assumption corresponds to maximum throughput according to ‘bang-bang’ strategy [7]. The weighting factor \( \alpha \) takes values from 0 to 1, specifying the acceptable degradation of throughput. When the factor is equal to zero, maximum fairness is achieved, while the unit corresponds to maximum throughput. Therefore, a trade-off between throughput and fairness is achieved through the parameter \( \alpha \). By selecting a high weighting factor \( \alpha \), throughput is maintained at a high value.

In our hybrid scheme, the transmission rates are discrete values. Thus, an additional constraint is needed in order to check if a rate \( R_n \) belongs to the set of available rates determined by the function (10). The following equality constraint is introduced:

\[
g(R_n) = \left| R_n - f^U \left( \frac{R_n}{R_p} \right) \right| = 0 \quad n = 1, \ldots, N \tag{16}
\]

It can be easily noted that the objective function in Equation (12) and the constraints (15) and (16) are nonlinear, while the other constraints are linear functions of the variables. A non-empty feasible set for the optimisation problem is already guaranteed by the resource controller. The power vector \( S_{\text{sum}} = [S_{\text{sum},1}, \ldots, S_{\text{sum},N}] \), which is derived by Equation (8) using the rates assumed by the resource controller, is chosen as initial vector in the optimisation problem.

After rate scheduling is finished in a frame, feedback information is sent back to the MT. It includes the time slot to transmit, the overall received power and the overall allocated rate. The MT is then free to decide how many and which OVSF codes to use, provided that it sends back to the BS the selected codes through the signaling channel (request slot). Our analysis, which is based on the total MT power instead of code power [2], helps solving fragmentation issues of the OVSF trees, such as code blocking [5], without involving the BS.

4. NUMERICAL RESULTS

The performance of the proposed scheme is evaluated by indicative simulations, where our approach is compared to other rate allocation schemes. The input parameters are denoted in Table 1. The maximum number \( U \) of
codes per MT is variable in order to investigate the effect of this parameter. Two services are simulated. The first service (RT) is a VoIP connection based on G.729 (8 kbps for encoding rate and 20 bytes for UDP packet size) with $E_b/N_0 = 2.54$ dB. Each UDP packet generation corresponds to a transmission rate per slot equal to 128 kbps. The corresponding requested rate $r_i$, which belongs to the discrete set of available rates, is found by Equation (10). The duration of the VoIP connection is exponentially distributed with the average equal to 180 sec. The second service (NRT) is a data application with the average equal to 1 MB. The interarrival time for both services is exponentially distributed with the mean size equal to 1 MB. The interarrival time for both services is exponentially distributed with the average equal to 5 min. The Round Robin algorithm is used for the classification of the requests inside each priority queue.

We present a snapshot of our simulation and in particular a specific slot. In this slot, three VoIP and two data users intend to transmit. The transmission window $w$ is equal to 2 for this configuration, thus both data users are allowed to transmit. For the solution of the optimisation problem, we use Matlab and the pattern search algorithm (Matlab Direct Search Toolbox). This algorithm is appropriate to solve complicated, nonlinear problems. The results are shown in Table 2. The derived rates are denoted as $(R_1, R_2, R_3, R_4, R_5)$ under the rate column, where indexes 1, 2, 3 and 4, 5 stand for VoIP and data users, respectively. The above rates and the throughput $t_r$ are given in units of $R_b$. The ‘NR sum’ is an abbreviation for the sum of normalised rates. The methods under comparison combine several modes of transmission (MC, VSF, hybrid MC-OVSF) and rate scheduling algorithms (throughput maximisation, ‘NR sum’ maximisation). For simplicity, they are denoted as MC (A), VSF max throughput (B), hybrid max throughput (C) and hybrid max ‘NR sum’ (D). Method D-x represents our proposal with x equal to the value of the parameter $\alpha$. In order to evaluate the fairness, we use the fairness index [8]

$$d_F = \frac{\left( \sum_{i=1}^{I} R_i \right)^2}{I \sum_{i=1}^{I} R_i^2}$$

where $I$ is the number of users and $R_i$ the allocated rate to user $i$. The index is positive and upper-bounded by 1. High index value means high fairness. In Table 2, the fairness index is calculated only for data users, since the requested rates are always allocated to VoIP users and data users share the remaining resources.

In all cases, the pattern search algorithm converges very quickly (up to four iterations) to a global solution. MC (A) leads to low throughput and under-utilisation of the resources, since each code channel uses the basic transmission rate. VSF max throughput (B) leads to higher throughput but less than hybrid max throughput (C). This is due to the fact that hybrid schemes have the flexibility to use more codes simultaneously. Moreover, in C, the throughput increases with the use of more codes. The disadvantage of this method is that it guides to unfair allocations and poor fairness indexes. By using ‘NR sum’ maximisation with $a=0$ (D-0), fair allocation takes place, with $d_F$ approximating unity, while a throughput degradation is observed compared to method C. Further increase on fairness can be achieved through a higher value on $U$. This increase does not occur at the expense of throughput, since the last remains stable after $U$ reaches a value ($U = 3$). Moreover, total fairness is achieved for D-0 method after a $U$ threshold ($U = 5$). In order to limit the throughput degradation, higher values of the parameter $\alpha$ (0.75, 0.80,

---

**Table 1. System parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>$W$</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Noise spectral density</td>
<td>$N_0$</td>
<td>$-174$ dBm/Hz</td>
</tr>
<tr>
<td>Intercell interference</td>
<td>$I_{inter}$</td>
<td>0.1 W</td>
</tr>
<tr>
<td>OVSF tree levels</td>
<td>$M$</td>
<td>9</td>
</tr>
<tr>
<td>Basic transmission rate</td>
<td>$R_b$</td>
<td>19.5 kbps</td>
</tr>
<tr>
<td>Max received power per MT n</td>
<td>$S_{max,n}$</td>
<td>1 W</td>
</tr>
<tr>
<td>Frame duration</td>
<td>$T_f$</td>
<td>10 msec</td>
</tr>
<tr>
<td>Slots per frame</td>
<td>$N_s$</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 2. Comparison of rate scheduling algorithms.**

<table>
<thead>
<tr>
<th>$U$</th>
<th>Rate ($R_b$)</th>
<th>NR sum $t_r$ ($R_b$)</th>
<th>$d_F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(5, 5, 5, 5)</td>
<td>0.2113</td>
<td>25</td>
</tr>
<tr>
<td>B</td>
<td>(8, 8, 256, 16, 18)</td>
<td>0.9180</td>
<td>296</td>
</tr>
<tr>
<td>C</td>
<td>(8, 8, 256, 18)</td>
<td>0.9296</td>
<td>298</td>
</tr>
<tr>
<td>C</td>
<td>(7, 7, 256, 22)</td>
<td>0.9330</td>
<td>299</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 8, 8, 96, 80)</td>
<td>0.9439</td>
<td>200</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 100, 88)</td>
<td>0.9573</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 96, 92)</td>
<td>0.9580</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 94, 94)</td>
<td>0.9581</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 149, 54)</td>
<td>0.9477</td>
<td>224</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 177, 42)</td>
<td>0.9421</td>
<td>240</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 203, 34)</td>
<td>0.9394</td>
<td>258</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 218, 30)</td>
<td>0.9371</td>
<td>269</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 241, 25)</td>
<td>0.9351</td>
<td>287</td>
</tr>
<tr>
<td>C</td>
<td>(7, 7, 256, 22)</td>
<td>0.9330</td>
<td>299</td>
</tr>
<tr>
<td>C</td>
<td>(8, 8, 256, 18)</td>
<td>0.9296</td>
<td>298</td>
</tr>
<tr>
<td>C</td>
<td>(7, 7, 256, 22)</td>
<td>0.9330</td>
<td>299</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 8, 8, 96, 80)</td>
<td>0.9439</td>
<td>200</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 100, 88)</td>
<td>0.9573</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 96, 92)</td>
<td>0.9580</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 94, 94)</td>
<td>0.9581</td>
<td>209</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 149, 54)</td>
<td>0.9477</td>
<td>224</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 177, 42)</td>
<td>0.9421</td>
<td>240</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 203, 34)</td>
<td>0.9394</td>
<td>258</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 218, 30)</td>
<td>0.9371</td>
<td>269</td>
</tr>
<tr>
<td>D-0</td>
<td>(7, 7, 241, 25)</td>
<td>0.9351</td>
<td>287</td>
</tr>
</tbody>
</table>

Copyright © 2009 John Wiley & Sons, Ltd.
Table 3. Sensitivity analysis and proof of transmission window concept.

<table>
<thead>
<tr>
<th>Users</th>
<th>Method C</th>
<th>Method D-0</th>
<th>Method D-0.80</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V, D)</td>
<td>( t_r (R_b) )</td>
<td>( d_e )</td>
<td>( t_r (R_b) )</td>
</tr>
<tr>
<td>(0, 2)</td>
<td>309</td>
<td>0.6985</td>
<td>246</td>
</tr>
<tr>
<td>(0, 3)</td>
<td>308</td>
<td>0.4641</td>
<td>194</td>
</tr>
<tr>
<td>(0, 4)</td>
<td>307</td>
<td>0.3468</td>
<td>175</td>
</tr>
<tr>
<td>(1, 2)</td>
<td>304</td>
<td>0.6562</td>
<td>232</td>
</tr>
<tr>
<td>(1, 3)</td>
<td>303</td>
<td>0.4355</td>
<td>188</td>
</tr>
<tr>
<td>(1, 4)</td>
<td>303</td>
<td>0.3270</td>
<td>172</td>
</tr>
<tr>
<td>(2, 2)</td>
<td>301</td>
<td>0.6193</td>
<td>220</td>
</tr>
<tr>
<td>(2, 3)</td>
<td>300</td>
<td>0.4114</td>
<td>182</td>
</tr>
<tr>
<td>(2, 4)</td>
<td>300</td>
<td>0.3083</td>
<td>168</td>
</tr>
</tbody>
</table>

0.85, 0.90, 0.95) can be used. In all cases, it can be shown that the throughput degradation is less than \((1 - \alpha) \times 100\%\), while the fairness index increases compared to method C.

In order to gain some insight in the sensitivity of the proposed scheme and test the transmission window concept, we vary the number of VoIP and data users (V, D) for the methods C, D-0, D-0.80 when \( U = 5 \). The results are shown in Table 3. Method C always gives the higher throughput, while method D-0 almost provides total fairness. Method D-0.80 limits the throughput degradation (less than 20%), while increasing the fairness index compared to C. Moreover, if we allow the transmission of more than \( w \) (\( w = 2 \)) data users in the slot, a high degradation on fairness in method C, D-0.80 and a high throughput degradation in method D-0 occur. Therefore, the transmission window concept is proved.

5. CONCLUSIONS

In this paper, a hybrid multirate MAC protocol, which combines both multicode (MC) and OVSF transmission, is presented. Initially, the minimum-power allocation problem is solved and the derived condition is used as a resource controller. The BS scheduler is then presented based on a double queue priority model, the DRA and ARA algorithms, the resource controller and the RA procedure. In the resource controller, we introduce the transmission window concept in order to reduce the interference and better utilise the system resources. The RA is formulated as a constrained optimisation problem, which tries to maximise the sum of normalised rates instead of throughput. A new optimisation constraint is used in order to deal with the discrete set of transmission rates that the hybrid scheme supports. It is shown that our algorithm has advantage compared to plain MC, VSF schemes and maximum throughput algorithms in terms of fairness. Maximum fairness is achieved by increasing the maximum number of codes per MT. By limiting the throughput degradation through a weighting factor \( \alpha \), we succeed a good trade-off between throughput and fairness. Moreover, our analysis focuses on MT level rather than code level, allowing the MT to select itself how many and which codes to use after the rate allocation. The proposed rate scheduling scheme can be applied not only to TD-CDMA systems as presented in this paper but also to pure WCDMA.

6. APPENDIX

For each terminal \( n \), Equation (5) forms a system of \( M \) equations.

\[
S_{m,n} = \frac{\gamma_n}{G_m} \left( \sum_{j=1}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W \right)
\]  

(A5)

We proceed with some elementary operations in order to eliminate the parameter \( m \) per terminal \( n \). We multiply Equation (5) by \( C_{m,n} \) and then we sum the respective parts of the \( M (m \in \{1, \ldots, M\}) \) derived equations. Thus,

\[
\sum_{m=1}^{M} C_{m,n} S_{m,n} = \gamma_n \sum_{m=1}^{M} C_{m,n} G_m \left( \sum_{j=1}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W \right)
\]  

(A1)

Putting the definitions of the overall received power \( S_{\text{sum},n} (1) \) and the overall transmission rate \( R_n \) of terminal \( n \) (2) into Equation (A1), yields

\[
S_{\text{sum},n} = \gamma_n \frac{R_n}{W} \left( \sum_{j=1}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W \right)
\]  

(A2)

The Equation (A2) forms a system of \( N \) linear Equations (\( n \in \{1, \ldots, N\} \)) in the power vector \( S_{\text{sum}} = \left[ S_{\text{sum},1}, \ldots, S_{\text{sum},N} \right]^T \).
Based on the above analysis, the initial system (5) of $M \times N$ equations is transformed to a system of $N$ equations. We use the methodology in Reference [3] to solve the system of $N$ equations. Equation (A2) yields the matrix equation

$$A S_{\text{sum}}^T = (I_{\text{inter}} + N_0 W) 1$$

(A3)

where

$$A = \begin{bmatrix}
\frac{W}{\gamma_1 R_1} & -1 & \cdots & -1 \\
-1 & \frac{W}{\gamma_2 R_2} & \cdots & -1 \\
\vdots & \vdots & \ddots & \vdots \\
-1 & -1 & \cdots & \frac{W}{\gamma_N R_N}
\end{bmatrix}$$

(A4)

and $1 = [1, 1, \ldots, 1]^T$. The index T stands for the transpose of the vector. Subtracting each row from the next gives

$$S_{\text{sum},(n+1)} = \left(\frac{W}{\gamma_n R_n} \right) + 1 \left(1 - \sum_j \frac{1}{\gamma_j R_j} + 1\right) S_{\text{sum},n}$$

(A5)

Substituting Equation (A5) into Equation (A2) and after some algebra, we have the Equation (8)

$$R_n = \frac{W}{\gamma_n} \sum_{j=1}^{N} S_{\text{sum},j} + I_{\text{inter}} + N_0 W$$

The power per code $S_{n,n}$ can be calculated based on the total MT power $S_{\text{sum},n}$, the definition of $S_{\text{sum},n}$ (1) and the Equations $G_1 S_{1,n} = G_2 S_{2,n} = \ldots = G_M S_{M,n}$. The last equations can be easily derived by Equation (5), if we multiply by $G_m$.

REFERENCES


AUTHORS’ BIOGRAPHIES

Panagiotis T. Vlachas received the Diploma degree in Electrical and Computer Engineering from the National Technical University of Athens (NTUA), Athens, Greece, in 2003. Since November 2003, he is a Ph.D. candidate and a Research Associate at the Computer Networks Laboratory of the School of Electrical and Computer Engineering at NTUA. His research interests are in the area of wireless communication networks, Radio Resource Management, Admission Control strategies, Packet Scheduling algorithms for 4G and heterogeneous mobile networks. He is a member of the Technical Chamber of Greece.
Eleni A. Kolokotroni graduated from National University of Athens in 2000 with a diploma from Faculty of Physics, School of Sciences. In 2003 she obtained her MSc on “Medical Physics—RadioPhysics” from the Faculty of Medicine, National University of Athens. Currently, she is a PhD candidate in the Microwave and Fiber Optics Laboratory of School of Electrical and Computer Engineering—National Technical University of Athens in cooperation with the Faculty of Medicine, University of Patras. Her research interests include communication systems, sensor networks, biological process modeling and bioinformatics. She is holder of the licentiates for practicing Medical Physics and Non-Ionizing Radiation and she is a member of the Union of Medical Physicists in Greece.

Elias Z. Tragos was born in Kalamata, Greece in 1981. He received his Diploma in Electrical and Computer Engineering from the School of Electrical and Computer Engineering (SECE) of the National Technical University of Athens (NTUA) in 2003, his MBA in Technoeconomics from the SECE of NTUA in 2006 and his PhD from the SECE of NTUA in 2009. He is currently a research associate at the Institute of Computer Science (ICS) of the Foundation for Research and Technology—Hellas (FORTH). He has been involved in the WINNER and WINNER II projects and in the WWI Cross Issues workgroups of System Architecture, System Interfaces and Validation and in various national projects. His research interests are in the area of mobile and wireless networks, network architecture and design, Radio Resource Management, mobility and policy based management and P2P networks. Dr. Tragos is also a Member of the Technical Chamber of Greece.

Michael E. Theologou received the degree in Electrical Engineering from Patras University and his Ph.D. degree from the School of Electrical and Computer Engineering of the National Technical University of Athens (NTUA). Since 1991 he has been with the School of Electrical and Computer Engineering of NTUA, where he is currently a Professor in the Communications, Electronics and Information Systems Department. He teaches Communication Networks, Computer Networks and Mobile and Personal Communications. His current research interests are in the fields of Mobile and Personal Communication Networks, Network Management, Quality of Service, Communication Service engineering. He has many publications in these areas.