Multirate Multiuser DS/CDMA with Genetic Algorithm Detection in Multipath Channels

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Abstract—This work analyses a heuristic algorithm based on the genetic evolution theory applied to multirate multicode (MC) direct sequence code division multiple access (DS/CDMA) multiuser detection (GA-MC-MuD) in multipath fading channels. Monte-Carlo simulation results, in two multirate conditions, showed that the detection based on GA is a viable option when compared with the optimum MuD (OMuD). Even under hostile channel conditions and severe system operation (loading and errors in the channel coefficients and amplitudes estimates) the GA-MC-MuD performance results are promising. The GA-MC-MuD algorithm complexity is determined and compared with the AWGN synchronous channels [2], [3] or flat channels [4].

I. INTRODUCTION
For most of the practical cases of engineering interest, MuD based on heuristic techniques result in almost optimum performance, i.e., very close to the performance reached by the OMuD [1], however with the advantage of smaller computational cost and detection time, an attractive trade-off between convergence speed and complexity. In spite of computational cost and detection time, an attractive trade-off between convergence speed and complexity. In spite of existence of several works using approximative procedures for the sub-optimum MuD, most of investigations are restricted to the AWGN synchronous channels [2], [3] or flat channels [4]. Very few works analyze the detection problem in frequency selective channels [5], [6]. Differently of [5], this work uses one-shot GA-MuD over all bits from all users in the same frame, considering multipath exponential power profile channels with errors in the parameters estimates. Additionally, the maximal rate combining (MRC) was used in order to find the initial candidate bits. Differently of [5] and [6], this work analyzes the performance of multirate systems.

II. DS/CDMA SYSTEM MODEL
The k-th user, belonging to the g-th MC group (from a total of G), transmits information using \( n_t^{(g)} = \frac{R}{R_t} \) parallel codes in the bit interval \( T \) in the form:

\[
b_k^{(g)} = [b_{k,1}, b_{k,2}, \ldots b_{k,m(g)}]^T
\]

with \( R_t^{(g)} = \) data rate of \( g \)-th MC group and \( R = \frac{1}{T} \) = basic rate, admitted as an integer sub-multiple of \( R_t^{(g)} \).

The information bits are spread in two steps. The MC channeling multirate scheme allows that all parallel channels of the same user are orthogonal; the spreading stage offers some multiple access interference (MAI) rejection and provides the identification of each DS/CDMA user. Assuming that the k-th user adopts BPSK modulation for all of its \( m_t^{(g)} \) waveforms, each transmitted signal can be expressed as [7]:

\[
u_k^{(g)}(t) = \sum_{i}^{m_t^{(g)}} b_k^{(g)}(i)s_{g}^{(g)}(i)\sqrt{P_{T,k}}\cos(\omega_c t - iT_{ch}(i))
\]

with the normalized channel coding waveform vector for the \( k \)-th user is defined by:

\[
s_{g}^{(g)}(t) = \frac{1}{\sqrt{N_C}} \left[ s_{g}^{(g)}(1), s_{g}^{(g)}(2), \ldots, s_{g}^{(g)}(N_C) \right]
\]

where the normalized channel coding waveform vector for the \( k \)-th user with length \( N_C \) given by:

\[
s_{g}^{(g)}(i) = \sum_{n=0}^{N_C-1} s_{g}^{(g)}(i) p_{T,n}(t - iT_{ch}(i)), \quad \text{for } n \in \{ \pm 1 \}
\]

where \( s_{g}^{(g)}(i) = \pm 1 \) is the channeling pulse shaping defined in the interval \( [0, T_{ch}(i)] \).

It will be assumed that for all MC users the correspondent channel coding waveform vector (II) is attributed from a unique set of Walsh-Hadamard (WH) sequences with length \( N_C \geq m_r^{(G)} \), attributing the first \( m_r^{(G)} \) codes to the \( k \)-th user with data rate \( m_r^{(G)} R \). As for the same MC user the preferential phase condition among WH sequences is maintained the generated interference will be virtually zero. Next the spreading is carried out using one sequence from a set of pseudo noise (PN) sequences; for the \( k \)-th MC user the band pass signal after the second spreading process results:

\[
x_k^{(g)}(t) = \sqrt{2P_{k,g}} \sum_j u_k^{(g)} s_k^{(g)}(t - jT)\cos(\omega_c t)
\]

where \( P_{k,g} = A_{k,g}^2/2 \) represents the power transmitted by the \( k \)-th user; \( \omega_c \) is the carrier frequency; \( s_k^{(g)}(t) \) the spreading sequence of the \( k \)-th user defined in the interval \([0, T)\) and zero outside by:

\[
s_k^{(g)}(t) = \frac{1}{\sqrt{N_P}} \sum_{n=0}^{N_P-1} p_{T,c}(t - nT_{c,k}) \xi_{k,m,n,g}(t), \quad \text{for } n \in \{ \pm 1 \}
\]

where \( \xi_{k,m,n,g}(t) = \pm 1 \) is the \( n \)-th channel of the PN sequence, which has length \( N_{P} = T_{c,k} \); used by the \( k \)-th user of the \( g \)-th group; \( T_{c} \) is the chip period which defines the DS/CDMA bandwidth; both shaping pulses \( p_{T,c} \) and \( p_{T,n} \) are assumed rectangular with unitary amplitude in the interval \([0; T_{c})\) and \([0; T_{ch}(i)]\), respectively, and zero outside. Considering the reverse channel and assuming a set of transmitted bits (frame) with \( I \) bits from each MC user through \( L \) independent paths with
Rayleigh fading, the base band received signal at the Base Station (BS) is given by:

\[ r(t) = \sum_{i=0}^{l-1} \sum_{k=1}^{K^{(g)}} \sum_{g=1}^{L} s_k^{(g)} g_k(t) \left( t - \tau_k^{(g)} \right) + h_k^{(i)} + \eta(t) \]  

(5)

where \( K^{(g)} \) is the number of physical active users belonging to the \( g \)-th multirate group, with \( K = K^{(1)} + K^{(2)} + \ldots + K^{(g)} + \ldots + K^{(G)} \) the number of physical users in the system, \( t \in [0, T] \), \( g_k(t) \in \{ \pm 1 \} \) is the transmitted information bit, \( s_k^{(g)} \) is the locally generated signature code adopted by the \( k \)-th user of \( g \)-th group, with the correspondent random delay given by \( \tau_k^{(g)} = \Delta_k^{(g)} + d_k^{(g)} \). This delay considers not only the asynchronous nature of data transmission \( d_k^{(g)} \) but also the propagation delay \( \Delta_k^{(g)} \) for the \( k \)-th user of the \( g \)-th group in the \( \ell \)-th path; \( \eta(t) \) represents the AWGN (Additive White Gaussian Noise) with bilateral power density given by \( N_0/2 \) and the channel impulsive response for the \( k, g \)-th MC user in the \( i \)-th bit interval can be written as:

\[ h_k^{(i)}(t) = \sum_{l=1}^{K} c_{k,l,g}^{(i)} \left( t - \Delta_k^{(i)} \right) \]  

where \( c_{k,l,g}^{(i)} = \delta_k^{(i)} e^{-j \phi_k^{(i)}} \) is the complex channel coefficient for the \( k \)-th MC user, \( \ell \)-path; it is assumed that the \( c_k \) phase has uniform distribution over \([0, 2\pi)\), \( \phi_k^{(i)} \in U(0, 2\pi) \), and the channel module \( \beta_k^{(i)} \) represents the small scale fading with envelope following a Rayleigh distribution. Additionally the channels gain were assumed normalized for all users, i.e., \( E \left[ \sum_{k,l,g} c_{k,l,g}^{(i)} \right]^2 = 1, \forall k \). Using vectorial notation, (5) can be re-stated as:

\[ r(t) = \sum_{i=0}^{l-1} s^T(t) a^{(i)} u^{(i)} + \eta(t) \]  

(6)

where: \( s(t) = \begin{bmatrix} s_1^{(1)}(t - \tau_{1,1}) & s_1^{(1)}(t - \tau_{1,2}) & \ldots & s_1^{(1)}(t - \tau_{1,L}) & \ldots & s_g^{(1)}(t - \tau_{g,1}) & s_g^{(1)}(t - \tau_{g,2}) & \ldots & s_g^{(1)}(t - \tau_{g,L})s_{K}^{(1)}(t - \tau_{K,1}) & \ldots & s_{K}^{(1)}(t - \tau_{K,L}) \end{bmatrix}^T \) is the PN spreading sequence matrix of all users; \( a = \text{diag} \left[ \sqrt{P_{1,1}} I, \sqrt{P_{2,1}} I, \ldots, \sqrt{P_{K,1}} I \right] \) is a diagonal matrix with the received amplitudes, considered constant along the \( f \) transmitted bits, including the channel path loss and shadowing effects; \( I_{L \times L} \) is an \( L \)-dimensional identity matrix; \( e^{(i)} = \begin{bmatrix} e_{K,1,1}^{(i)}, \ldots, e_{K,1,L}^{(i)}, e_{K,2,1}^{(i)}, \ldots, e_{K,2,L}^{(i)}, \ldots, e_{K,1,1}^{(i)}, \ldots, e_{K,1,L}^{(i)} \end{bmatrix}^T \) is a diagonal matrix with the channels gain, and the vector with the information bits spread by the MC channeling codes is given by \( u^{(i)} = \begin{bmatrix} u_1^{(i)}, u_2^{(i)}, \ldots, u_L^{(i)} \end{bmatrix}^T \) with \( u_l^{(i)} \) containing the replies (tripath) of the channelled \( i \)-th bit [given by (2)] of the \( k \)-th MC physical user with dimension \( 1 \times L \). For the sake of simplicity but without losing generality the random delays were considered ordered, i.e., \( 0 = \tau_{1,1} \leq \tau_{1,2} \leq \cdots \tau_{1,L} \leq \tau_{2,1} \leq \cdots \leq \tau_{K,1} \leq \cdots \leq \tau_{K,L} \leq T \). For multipath channels and the MC channeling scheme the Rake receiver consists in a bank of \( KD \) filters matched to the spreading sequences of the MC physical users, with path diversity \( D \leq L \), followed by the second despreader (channeling) in order to recover the \( n^{(g)} \) simultaneously transmitted bits of \( k \)-th MC physical user corresponding to the \( \ell \)-th multipath component (finger), sampled at the end of basic period \( T \) of \( i \)-th bit interval can be expressed as:

\[ y_{k,\ell,g}^{(i)}[m] = \frac{1}{\sqrt{N_c}} \int_0^T r(t) s_k^{(g)}(t - \ell T - \tau_k^{(m)}) c_{k,m,g}(t) dt \]

\[ = \frac{1}{\sqrt{P_{k,m}^{'}}} \delta_{k,\ell,g}^{(i)} + S_{k,m,\ell} + I_{k,m,\ell} + n_{k,\ell,g} \]

where \( m = 1, 2, \ldots, m^{(g)} \), the first term corresponds to the desired signal, the second to the self-interference (SI); the third to the MAI over the \( \ell \)-th multipath component of \( m \)-th parallel channel of \( k \)-th user; and the last to the filtered AWGN. The SI and MAI terms depend on the partial correlation function, which in the double spreading case results:

\[ R_{u,m,k,n}(\tau, i) = \int_0^T s_k^{(g)} s_u^{(m)}(t) s_k^{(g)}(t + \ell T + \tau) dt \]

with the indexes \( m \) and \( n \) showing the respective parallel channels of \( u \)-th and \( k \)-th physical MC users.

Using vectorial notation the matched filters bank outputs for the \( i \)-th bit interval, considering \( D \) branches of diversity are given by the equations (7)–(10). The matrices \( R[0] \) and \( R[1] \), both with dimension \( DK \times DK \), are defined by the elements:

\[ R_{ij}[0] = \begin{cases} 1, & u = k \text{ and } m = n \\ R_{u,m,k,n}(\tau_{uk},0), & u < k \\ R_{u,m,k,n}(\tau_{uk},0), & u > k \\ R_{u,m,k,n}(\tau_{uk},0), & u = k \text{ and } m < n \\ R_{u,m,k,n}(\tau_{uk},0), & u = k \text{ and } m > n \\ 0, & u \geq k \end{cases} \]

\[ R_{ij}[1] = \begin{cases} R_{k,u,m,n}(\tau_{uk},0), & u < k \\ 0, & u \geq k \end{cases} \]

where \( i = u,m; j = k,n \) and \( K_u = \sum_{g=1}^G K^{(g)} m^{(g)} \) is the number of virtual users in the MC DS/CDMA system. The Rake receiver combines all available signals from the matched filters bank outputs of each user (finger) in a coherent mode and weighted by the respective channel gain [8]. The maximal ratio combiner (MRC) combines the signals from the \( D \) correlators as:

\[ z_k^{(i)} = \sum_{g=1}^D \text{Re} \left\{ \frac{y_{k,\ell,g}^{(i)}}{\beta_{k,\ell,g}^{(i)}} \right\}, \text{ followed by an abrupt decision circuit, } b_k^{(i)} = \text{sign}(z_k^{(i)}) \]

The best performance among MuD is reached with the OMUD [1], which is based on the maximum likelihood (ML) estimation strategy. In this context the ML vector that should be found by the OMUD is the Expectation vector, \( y^{(i)}(t) \), to find the ML, vector \( b \) is equivalent to select the vector of bits \( B \) which maximizes the likelihood function (LLF) [1]:

\[ \Omega(B) = 2 \text{Re} \left\{ B^T c_H A y \right\} - B^T C A R A C^H B \]

(12)

where the diagonal matrices of channel coefficients and amplitudes, both with dimension \( K_u D \), are defined, respectively, by:

\[ C = \text{diag} \left[ c_0^{(0)}, c_1^{(1)}, c_2^{(2)}, \ldots, c^{(l-1)} \right] \]

and \( A = \ldots\]

129
\[
\mathbf{y}^{(i)} = \begin{bmatrix}
\mathbf{y}_1^{(i)} & \mathbf{y}_2^{(i)} & \ldots & \mathbf{y}_1^{(D)} & \mathbf{y}_2^{(D)} & \ldots & \mathbf{y}_k^{(1,m(g))} & \mathbf{y}_k^{(2,m(g))} & \ldots & \mathbf{y}_k^{(D,m(g))}
\end{bmatrix}
\]
(7)

\[
\mathbf{b}^{(i)} = \begin{bmatrix}
\mathbf{b}_1^{(i)} & \mathbf{b}_2^{(i)} & \ldots & \mathbf{b}_1^{(D)} & \mathbf{b}_2^{(D)} & \ldots & \mathbf{b}_k^{(1,m(g))} & \mathbf{b}_k^{(2,m(g))} & \ldots & \mathbf{b}_k^{(D,m(g))}
\end{bmatrix}^T
\]
(8)

\[
\mathbf{e}^{(i)} = \begin{bmatrix}
\mathbf{e}_1^{(i)} & \mathbf{e}_2^{(i)} & \ldots & \mathbf{e}_1^{(D)} & \mathbf{e}_2^{(D)} & \ldots & \mathbf{e}_k^{(1,m(g))} & \mathbf{e}_k^{(2,m(g))} & \ldots & \mathbf{e}_k^{(D,m(g))}
\end{bmatrix}
\]
(9)

\[
\mathbf{a}^{(i)} = \begin{bmatrix}
\mathbf{a}_1^{(i)} & \mathbf{a}_2^{(i)} & \ldots & \mathbf{a}_{k,m(g)}^{(i)}
\end{bmatrix}
\]
(10)

with \( k \in K^{(g)} \) and \( \mathbf{I}_{D \times D} \) is the identity matrix with dimension \( D \).

The estimates from the Rake receiver outputs are adopted as an initial individual. The other members of the first population \( B \) are obtained from the initial individual with convenient perturbations [3], [5]. In the MuD context the aptitude is measured through the LLF function (12) and it is directly responsible for the death or life of individuals. The mating pool size (M) should be selected in order to guarantee the convergence velocity and the final solution quality [11]. For the MuD problem \( M = 0.1p \) was adopted. In this work, the selection process chooses the best \( M \) individuals from the population \( p \) as the parents for the next generation. For the GA-MC-MuD genetic operators, we adopted the uniform crossover [12] with crossover probability \( p_c \) and the mutation based on noise: \( \text{new}_\text{individual} = \text{sign} \left( \text{individual} + N(0, \sigma^2) \right) \), where \( N(0, \sigma^2) \) represents a Gaussian distribution with standard deviation \( \sigma \) and expectation zero. The standard deviation is strongly related with the mean rate mutation [3].

This work uses a replacement strategy called global elitism, where only the best \( p \) individuals from the joint population of parents and offsprings are maintained for the next generation. Finally, the optimization process is finished after a fixed number of generations (\( G_T \)).

### III. GENETIC ALGORITHM

A pseudo code for the GA-MC-MuD is described below. For a systematic analysis considering various heuristic MuD approaches in a single rate DS/CDMA over AWGN and flat Rayleigh channels see [4], and for multipath Rayleigh channels see [6]. The GA-MC-MuD total search universe will be characterized by all possible combination of received data bits that present the same bit for all D processing branches, i.e., \( \mathbf{b}_n^{(i)} = \mathbf{b}_{n+1}^{(i)} = \ldots = \mathbf{b}_n^{(D,g)} \in \{ \pm 1 \} \). This work uses an adapted equation in order to find the population size for the MuD problem based on [10]:

\[
p = 20 \cdot \left[ 0.3454 \left( \sqrt{\pi (K_n \cdot T - 1)} + 2 \right) \right]
\]
(14)

where the operator \( \lfloor x \rfloor \) returns the greatest integer not larger than \( x \). This equation is calculated in the GA initialization stage and maintained constant in all generations.

### IV. NUMERICAL RESULTS

In the Monte Carlo computational simulations the following parameters were adopted: Walsh-Hadamard channeling sequences with length \( N_C = 8 \); random PN spreading sequences with processing gain \( N_{PN} = T/T_c = 400 \); slow fading Rayleigh channel with three paths, where the second and third are delayed by 12T_c and 24T_c from the first, respectively; exponential delay-power profile with \( E \left[ \beta_2^T \right] = 0.8047 \), \( E \left[ \beta_2^2 \right] = 0.1625 \) and \( E \left[ \beta_2^3 \right] = 0.0328 \). All \( K \)
users were considered with an uniformly distributed velocity in the interval $[0; v_{max}]$, resulting in a maximum Doppler frequency of $f_d = \frac{v_{max}}{c} \approx 185 \text{ Hz}$ for a carrier frequency of $f_c = 2 \text{GHz}$; the adopted Rake diversity is $D = L = 3$ and the bandwidth of the system was adopted equal to $BW = 3.84 \text{MHz}$. In order to simulate different types of possible services two systems were considered where the users transmit with data rates $8R, 4R, 2R$ and $R$, where the basic data rate is $R = 9.6 \text{kbps}$, as described in Table I. For the two simulated scenarios the total number of virtual users was fixed as $K_v = m(1) \cdot K^{(1)} + m(3) \cdot K^{(2)} + m(3) \cdot K^{(3)} = 24$.

<table>
<thead>
<tr>
<th>Service</th>
<th>Phys. Users</th>
<th>Rate</th>
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<tbody>
<tr>
<td>System 1</td>
<td>System 2</td>
<td></td>
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<tr>
<th>Main Parameters of the GA-MC-MuD.</th>
<th>Rate</th>
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<tbody>
<tr>
<td>$p_{G}$</td>
<td>$p_{m}$</td>
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<tr>
<td>140</td>
<td>1.5%</td>
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<tr>
<td>$p_{G}$</td>
<td>$p_{m}$</td>
</tr>
<tr>
<td>140</td>
<td>1.52%</td>
</tr>
</tbody>
</table>

Table II

The transmitted powers and users’ delay are admitted as known in the receiver but, in order to test the algorithm robustness, errors are introduced in the channel parameters estimates (module and phase of channel coefficients). Finally a perfect power control scenario was assumed, i.e., $P_1 = P_2 = \ldots = P_{K_v}$. Errors were introduced separately and jointly being modeled through uniform distributions: $\beta_{k, \ell} \sim U[1 \pm \epsilon_{\beta}] \cdot \beta_{k, \ell}$ and $\phi_{k, \ell} \sim U[1 \pm \epsilon_{\phi}] \cdot \phi_{k, \ell}$.

Fig. 1 to Fig. 4 show the performance as a function of signal to noise ratio ($\gamma$), considering perfect estimates (Fig. 2 and 4) and with errors in the channel coefficients (Fig. 1 and 3), where $\epsilon_{\beta} = \epsilon_{\phi} = 0.10$. Even with channel estimates errors of the order of 10%, the BER for the GA-MC-MuD algorithm approaches the SuB performance, showing a huge performance gain in confront with the Rake receiver, for the evaluated data rates.

Fig. 2 shows the GA-MC-MuD algorithm convergence curve for the system 1: this graph expresses the performance evolution toward the optimum solution (obtained via OMuD) performance as a function of computed generations. With very few generations ($G_T \approx 25$ for the three simulated data rates) the GA-MC-MuD algorithm is able to find the near-optimum solution that means a huge complexity reduction when compared with the OMuD approach. This reduction can be computed comparing the number of tested candidates (visited search universe) by the two algorithms. After $G_T = 40$ generations the GA-MC-MuD has tested $p_{G_T} = 5,600$ candidates and the OMuD need to test $2^{K_v \cdot I \cdot D \cdot M_1} = 1.4 \times 10^{36}$.

Fig. 3 shows the GA-MC-MuD performance for the system 2. Two high data users are considered in this case. Even in this case with greater MAI and channel estimates errors of the order of 10%, the mean performance after $G_T = 40$ generations is very close to the SuB performance, for the three evaluated data rates.

Finally, Fig. 4 shows the GA-MC-MuD algorithm convergence curve for the system 2 as a function of computed generations. Increasing the number of users and the received power from all users by $2dB$ (in comparison with the conditions used in Fig. 2) it can be see that with few generations ($G_T = 40$) the algorithm reaches the optimum point (or near to the optimum) implying in a huge complexity reduction when compared with the OMuD algorithm.

In robustness terms against channel coefficient errors estimates, Monte-Carlo simulation results show that even with simultaneously module and phase estimates errors, about up to 10%, the GA-MC-MuD reaches better performance than those obtained with the Rake detector in the absence of errors, evidencing its tolerance to channel estimates errors. The GA-MuD (single rate) is more sensitive to phase errors than to module errors (not shown here; for details, see [6]).

V. Computational Complexity

In order to obtain the complexity reduction of the GA-MC-MuD algorithm in relation to the OMuD in a more precise form is necessary to express both complexities in terms of the number of relevant float point operations [14]. With this objective in mind we should compute the number of operations for the cost function calculation (12). For this purpose the set of operations $F_1 = c^{H}A^T V$ and $F_2 = c \cdot R_A V_A^C H$ can be obtained before the optimization loop of each algorithm. For each test of candidate solution $F_1 B$ and $B^T F_2 B$ are computed which in terms of operations is equivalent to $(K_v \cdot I \cdot D)^2 + 2K_v \cdot I \cdot D$ multiplications and one transposition of order $K_v \cdot I \cdot D$. For the OMuD the number of operations increases exponentially with the number of users, i.e., $O \left(2^{K_v \cdot I \cdot D} \right)$. In a more precise form, $2^{K_v \cdot I}$ bit generations of order $K_v \cdot I \cdot D$ and $2^{K_v \cdot I}$ cost function calculations are needed for the simultaneous detection of the set with $I$ bits from each of $K_v$ virtual users. For the GA-MuD the number of operations increases depending of the relation $O \left( p_{G_T} (K_v \cdot I \cdot D)^2 \right)$, being computed $3p_{G_T} + p - 1$ bit generations of order $K_v \cdot I \cdot D$, $M_G$ selections of order $K_v \cdot I \cdot D$, $p_{G_T}$ calculations of the cost function, $3p_{G_T}$ vector ordinations of order $K_v \cdot I \cdot D$, $p_{G_T}$ vector comparisons of order $K_v \cdot I \cdot D$ and $p_{G_T}$ vectors change of order $K_v \cdot I \cdot D$. As the numerical values of the variables $K_v$, $I$, $D$, $p$, $G_T$ and $M$ are identical for the two systems (1 and 2) we obtain the same computational complexity value for the two algorithms in these simulated conditions. In this case

1Theoretical number, not computable with the actual personal computer technology.
the OMuD detector needs to compute $1.72 \times 10^{43}$ operations in order to detect a set of $I$ bits for each one of the $K_v$ virtual users. In contrast, the GA-MC-MuD needs only $≈ 7.26 \times 10^6$ operations for the same detection, resulting in a great complexity reduction.

VI. CONCLUSIONS

For the physical users distributed in three transmission rates, the GA-MC-MuD receiver performance in multipath Rayleigh fading channels approaches the OMuD limit in a perfect parameters estimates condition. With errors in the parameters estimation the GA-MC-MuD showed an excellent performance yet, with the advantage of a huge complexity reduction in comparison with the OMuD, making its implementation feasible in the base stations of 3G and 4G cellular systems. The GA-MC-MuD has a relative immunity against errors in the estimates of channel coefficients and great robustness against errors in the estimates of amplitudes.

REFERENCES