Heuristic Multiuser Detectors: A DSP Implementation Perspective

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Abstract: This work investigates issues concerning the computational complexity of multiuser receivers in direct sequence code division multiple access (DS/CDMA) systems based on heuristic techniques and implemented on commercial platform for digital signal processing (DSP) (*Texas TMS320C6713*). The multiuser detection (MuD) algorithms which were implemented in baseband are based on the heuristic local search (LS) and simulated annealing (SA) approaches. Figures of merit regarding the bit error rate (BER) performance versus computational complexity trade-off are evaluated as a function of the system loading increasing (number of active users per processing gain); as a result, a methodology for the design and implementation of a baseband multiuser receiver structure using DSP platform is developed as well.

Key–Words: DSP, DS/CDMA, MuD, heuristic algorithms, computational complexity, performance-complexity tradeoff.

1 Introduction

In DS/CDMA systems, the limitation of performance and system capacity is mainly the result of multiple access interference (MAI). It becomes substantial when the number of users grows and/or when power disparities, namely near-far ratio (NFR), increases. The conventional detection considers all interfering users as noise leading a reduction in system capacity (throughput) and performance. Against this background, the well established solutions to increase simultaneously CDMA system capacity and performance when MAI increasing is a set of methods, ranging from the use of diversity[1] to the use of more efficient detection methods, named multiuser detectors (MuD), capable of utilizing the information of interfering users to improve the detection of user of interest [1].

The search for greater mobility associate to high transmission rates characteristics have meant that new multiple access technologies for transmission/reception were developed mainly aiming at the optimization of such systems. In this sense, for a minimum quality of service (QoS) to be met for each class of user, multiuser detection is a promising strategy for DSP implementation, just to use the information from the interfering users in the detection process, effectively reducing MAI, and resulting in improved performance compared to conventional detector [2] at a moderate computational complexity cost.

The MuD is based on the maximum likelihood (ML) function which expresses the probability of the observed event as a function of the parameter to be estimated [3]. Thus, multiuser detection based on ML function consists of a matched filter bank (MFB) followed by a ML sequence detector, which produces a maximum likelihood sequence, $\widehat{\mathbf{b}} = \left[\widehat{b}_1, \widehat{b}_2, \widehat{b}_3, ..., \widehat{b}_K\right]$, for the transmitted sequence. Therefore, the vector $\widehat{\mathbf{b}}$ is estimated to maximize the probability of the data sequence have been transmitted since the signal was received. This probability is called the joint *a posteriori* probability, $P_r\left(\mathbf{b}|r\left(t\right), \forall t\right)$, with the assumption of all transmitted messages are equiprobable [4].

Therefore, the bit error rate (BER) performance for the ML detector is optimum. However, to achieve this performance it is necessary a high implementation complexity. Such complexity increases exponentially with the number of users, making impossible the implementation of the ML detector, since an exhaustive search becomes impractical when the number of users grows. The use of heuristic algorithms adapted to the MuD problem, allows to obtain a very near ML performance, but at moderate computational complexity. Thus, heuristic algorithms can reduce the complexity in problems applied to wireless commu-

[1]Spatial frequency, micro-and macro-diversity among others

nication systems and simultaneously provide greater speed in achieving near-optimal results making the use of heuristic algorithms extremely interesting.

The digital signal processing (DSP) have been very attractive alternative currently employed in the implementation of multiple access systems, specially in the implementation of multiuser detectors at baseband receiver side. The DSPs may be employed in various areas as well as for specific processing, where you want to find adaptive solutions to a particular problem. Furthermore, the real-time simulation process is an area that has been extensively studied and developed over the years, with several programming works for process control. Thus, the limitation of time processing issue became a problem to be solved, because in order to ensure a real-time response at high level becomes a complex task, especially for systems with DSPs where certain data rates must be guaranteed [5].

The use of DSP platforms for the multiuser detectors implementation in DS/CDMA systems were previously reported in [6], [7]. In [6], the MuD implementation and channel parameter estimation in wideband CDMA (WCDMA) systems have been reported. The adopted multiuser detection technique was based on the algorithm Differencing Multistage. For real time detection procedure, it was used a fixed-point DSP platform, while for channel parameters estimation a floating-point DSP platform was used due to the greater complexity involved in the operations of the estimator. It is shown that the best optimization technique gave up working with the assembly code in critical regions of the algorithm, as multiplications between matrices of large dimensions. This procedure resulted in a significant improvement in processing time, both the estimator as the detector.

An implementation of multiuser detector based on parallel interference cancelation (PIC) technique with channel estimator for WCDMA systems was made in [7] using a fixed-point DSP platform. Beyond the implementation, the analysis was carried out considering different modulation schemes. The results show that the PIC and channel estimator implementation in fixed-point DSP platform is fully capable to achieve a marginal loss of performance in relation to a floating-point DSP implementation. The topology solution suggested in this work consists on the use of multiple DSP platforms, one for each active user in the system, and a central DSP for the PIC processing, bringing a significant performance boost to the system.

Recently, heuristic algorithms have been used in the channel parameters estimation [8], showing interesting performance when used in conjunction with Bayesian techniques, such as Particle Filter [9]. So, the effectiveness of the heuristic algorithms in various problems involving wireless communications have been demonstrated in last couple of years.

Hence, in this work, special attention is payed to the issues concerning the computational complexity of DS/CDMA multiuser baseband receivers. These MuDs are based on heuristic techniques and have been implemented using the *Texas TMS320C6713* commercial DSP platform. The implemented baseband MuD algorithms were based on the heuristic local search (LS) and simulated annealing (SA) approaches. Implementation issues, as well as the methodology for the design/implementation of a baseband MuD receiver using DSP platform are discussed in the sequel.

2 Model System

In this section, the equivalent base-band transmitter, conventional detector (CD), yet named single-user detector (SuD), and heuristic multiuser detectors (Heur-MuD) using 1-optimum Local Search (1-opt LS) algorithm, and simulated annealing (SA) algorithm are described. Among these, the two heuristic multiuser detectors (1-LS-MUD and SA-MUD) were implemented in DSP. The DS/CDMA performance was analyzed considering both channels, synchronous AWGN and Rayleigh flat channel. K is the number of users, N the processing gain, and L the system loading.

Assuming binary phase shift keying modulation and flat fading channel, the continuous-time baseband DS/CDMA received signal can be described such as:

$$r(t) = \sum_{k=1}^{K} A_k b_k s_k(t-\tau_k) * h(t) + \eta(t), \ t \in [0, T_b] \tag{1}$$

where A_k is the amplitude of the received signal for the kth user, related to $E_k = P_k T_b = A_k^2 T_b$, where E_k is the bit energy, P_k been the received power for the k-th user, and T_b is the bit period[2]. $b_k \in \{-1, +1\}$ is the transmitted data bit for the k-th user, assumed equiprobable and independent; $h(t)$ is the impulse response of the channel, and $\eta(t)$ the continuous-time AWGN noise, that represents the thermal noise with bilateral density power equal to $N_0/2$. Besides, since it was assumed synchronous system under non-selective frequency channel, so, $\tau_k = 0$, $\forall k$, and characterized by a Rayleigh flat channel:

$$h(t) = c_k(t) \cdot \delta(t) = \beta_k(t) e^{j\phi_k(t)} \cdot \delta(t) \tag{2}$$

where $c_k(t)$ indicates the complex channel coefficient in continuous-time for the k-th user, $\beta_k(t)$ denotes the

[2] Adopted without loss of generality, as normalized

module of c_k, with a Rayleigh statistical distribution, and $\phi_k(t)$ is the phase of c_k, with an uniform distribution between $[0, 2\pi)$. At the MFB output, the signal can be expressed as:

$$y_k = \int_0^{T_b} r(t)\, q_k(t)\, dt = A_k b_k c_k + \sum_{j \neq k} A_j b_j c_j \lambda_{k,j} + n_k \quad (3)$$

where $\lambda_{k,j} = \frac{1}{T_b} \int_0^{T_b} s_k(t) s_j(t)\, dt$ denotes the normalized cross-correlation between the k and jth users, and n_k is the filtered AWGN noise for the k-th user.

The adopted strategy to solve the MUD problem through heuristic techniques, analyzed in [1, 2], consists in finding a better solution using a cost-function based on the ML criterium and can be written as:

$$\mathcal{F}(\vartheta) = \Re\{2\mathbf{y}^T \mathbf{C}^H \mathbf{A} \vartheta - \vartheta^T \mathbf{C}\mathbf{A}\mathbf{R}\mathbf{A}\mathbf{C}^H \vartheta\} \quad (4)$$

where $\mathbf{y}$ is the the MFB output vector (before the abrupt decision), $\mathbf{C}$ is the diagonal matrix of coefficients of the channel; $\mathbf{A}$ is the matrix of amplitudes of the received signals, $\Re\{\cdot\}$ is the real operator, and $\mathbf{R}$ is the correlation matrix, given by:

$$\mathbf{R} = \begin{bmatrix} \lambda_{1,1} & \lambda_{1,2} & \cdots & \lambda_{1,K} \\ \lambda_{2,1} & \lambda_{2,2} & \cdots & \lambda_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{K,1} & \lambda_{K,2} & \cdots & \lambda_{1,K} \end{bmatrix} \quad (5)$$

In the block diagram of Figure 1, the heuristic algorithm is represented by the block (e). Hence, the HEUR-MUD is made up of all the blocks (c) and (d), which form the CD, along with the block (e) representing the heuristic multiuser DS/CDMA detection strategy, described in [10, 11].

3 Computational Tools

The computational tools used in the development of the MuD detectors are MATLAB® from Mathworks and Code Composer Studio (CCS®), associated with the digital signal processing platform. The signal processor TMS320C6713, Texas Instruments, used in this work is part of a development kit called C6713 DSP Starter Kit (DSK), and belong to the DSP platform developed by Spectrum Digital Inc.[3], which integrates a DSP, and a series of components designed to optimize its capacity. Such computational tools, together with the DSP platform (hardware) were employed in solving the MuD problem.

The CCS® is a software designed by the Texas Instruments for the development of programs and DSP interface models that it manufactures, includes tools for code generation, and graphical capabilities, also provides support for debugging of real-time data, through the real-time data exchange (RTDX) tool [12].

The RTDX provides continuous visibility into operations in DSP platform, transferring data between a host computer and target devices without interfering with the applications made in the target, i.e., without interruption of processing in the target [13].

In the RTDX tool, there are two channels for sending and receiving data between a client application on the computer and the target platform through a combination of hardware and software components. The host is the computer and the target is the C6713 DSK platform, and managed through CCS®. The client application in the host is the MATLAB® and the destination device in the target is the DSP processor. In this configuration, the creation and enabling of the input and output channels of RTDX should be made in both applications, MATLAB® and CCS®. Once created, the channels can transmit data from the client application to the target device and vice versa. However, the DSP must be active to be able to exchange this data in real-time, where there is no interruption of processing.

Aiming at a time processing optimization, it was created in MATLAB® functions for the automation of certain routines in each multiuser detection trial; as a consequence, manual commands were not required to compile and load the project in each processing trial. Thus, the DSP plataform were able to perform various receiver signal processing and detection consecutively without having to compile/load the project in CCS®. As a result, the time spent in these trials was optimized since in each of these trials it would be required the compilation and loading of new parameters into the processor.

4 DSP Implementation Methodology

This section describes the methodology used in the formulation, characterization and implementation in DSP of the analyzed DS/CDMA subsystems. In this work, all numerical simulations are based on Monte Carlo simulation (MCS) method. The estimated amount of trials to be carried out in each operation system scenario (for specific signal-noise ratio, number of users, channel type and so on), i.e., the minimal number of transmitted bits at each user, was made considering the average number of transmitted bit under single-user scenario, assuming for instance at least 10 bit errors, characterizing the single-user bound (SUB) performance.

[3] http://www.spectrumdigital.com

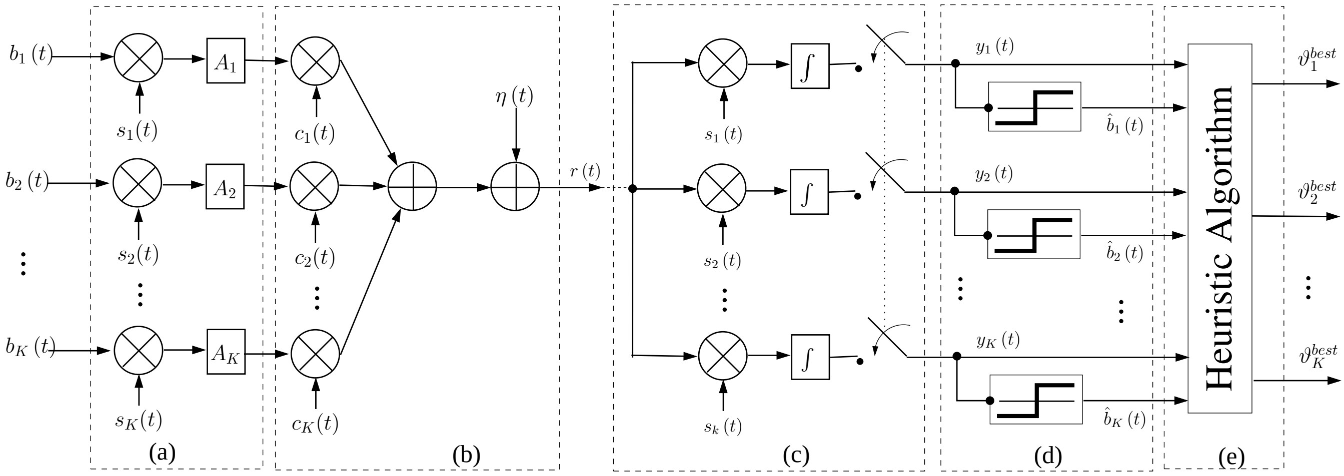


Figure 1: Baseband DS/CDMA system with HEUR-MUD: a) Transmitter; b) Rayleigh Flat Channel; c) 1st stage MFB; d) Hard decision with derivation point of the MFB estimates; e) Heuristic Algorithm.

The baseband transmitter has been described only in Matlab, while the HEUR-MUDs based 1-LS and SA algorithms were described in Matlab and implemented through the C6713 DSP platform. Despite the CD being implemented in DSP as part of HEUR-MUD, its output vector containing a data estimated bit for each user will not be sent to Matlab for analysis of the results due to the focus of the work is on the implementation of heuristic multiuser detectors. Thus, for the implemented HEUR-MUD only the estimated bits vector from DSP is sent to Matlab in order to generate the figures of merit [10] discussed in Section 5.

4.1 DS/CDMA Baseband Transmitter

At the transmitter side. described in MatLab language, it was generated the data bit stream for each user made randomly and with equal probability of antipodal bits ("1" or "-1"), i.e., BPSK modulation was assumed. Random spread sequences was generated with a condition that does not occur identical sequences, and spread spectrum of data bits was obtained and the baseband DS/CDMA signal is sent to the receiver through a AWGN simulated channel.

4.2 Baseband Wireless Channel

The physical propagation channel, represented by the multiplicative noise, was simulated based on the Modified Jakes model [14]. We adopted a number of 36 oscillators, carrier frequency of $3GHz$, and maximum mobile speed of $120Km/h$. This implies in a maximum Doppler frequency of $333.33Hz$. For the channel parameters, they were simulated the following scenarios: a) perfect estimate; b) channel error estimates (CEE) of 1% to 15%, introduced following Gaussian distributions, according to:

$$\widehat{c_k} = \widehat{\beta_k}\, e^{j\widehat{\phi_k}} \tag{6}$$

$$\widehat{\beta_k} = \mathcal{N}\left(\beta_k, \frac{\varepsilon_{\%}^{\text{mod}}}{100}\right) \tag{7}$$

$$\widehat{\phi_k} = \mathcal{N}\left(\phi_k, \frac{\varepsilon_{\%}^{\text{phase}}}{100}\right) \tag{8}$$

where $\widehat{c_k}$ indicates the imperfect channel complex coefficient for the k-th user (with errors in the estimates), $\widehat{\beta_k}$ and $\widehat{\phi_k}$ the phase and module, respectively, of $\widehat{c_k}$. The variables $\varepsilon_{\%}^{\text{mod}}$ and $\varepsilon_{\%}^{\text{phase}}$ indicate the percentage errors stipulated for the modulo and phase of the channel coefficients, respectively.

Hence, these parameters are generated in MATLAB® and then transmitted to the DSP platform (through RTDX in CCS®) in order to evaluate the HEUR-MUD performance under different channel and operation system conditions.

4.3 DS/CDMA Baseband Receiver

The baseband receiver subsystem was evaluated under two different approaches: the first one was described entirely in MATLAB® language in order to provide a reference for comparative basis. However, the focus in this subsection shall be given to the second baseband receiver subsystem implemented into the DSP platform. Som the baseband DS/CDMA receiver was described through language C under CCS® tool. Specific functions for addition, multiplication of matrices, also function for each heuristic algorithm detection were created and implemented in the DSP platform. All these functions were stored in a library and added to the project in the CCS®.

Figure 2 illustrates a block diagram of the DS/CDMA system developed through RTDX communication between MATLAB and DSP.

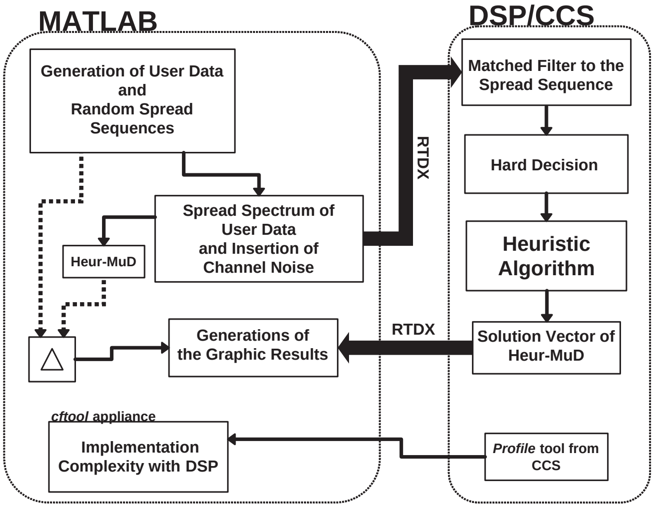


Figure 2: Block diagram for the DS/CDMA system, emphasizing the HEUR-MUD description, described through C language in MATLAB and DSP platform.

5 Performance × Complexity Trade-off

5.1 Heur-MuD Performance

This section brings results for the main figures of merit of the HEUR-MUDS implementation in DSP. In general, since different HEUR-MUD carry out same (or very close) performance, herein we have analyzed the BER performance results for the 1-LS-MUD under AWGN channels, while for Rayleigh flat channels, we have chosen to show the BER performance for the SA-MUD.

5.1.1 1-LS-MUD – AWGN Channel

To analyze the performance of the LS algorithm, we have adopted a processing gain $N = 15$, number of users $K = 12$ (i.e., system loading $L = K/N = 12/15 = 0.8$), and an $E_b/N_0[dB]$ range of 0 to $8dB$, as indicated in Figure 3. Note that due to high system loading, there is an considerable gap between the performance of 1-LS-MUD and SUB. However, the BER difference from 1-LS-MUD and CD is more prevalent.

Furthermore, Figure 3 describes the robustness of the 1-LS-MUD to the near-far effect. This figure of merit was performed considering a number of interest users $K_{\text{target}} = 4$, number of interfering users $K_{\text{interfer}} = 8$, $N = 15$, fixed $E_b/N_0 = 7$ dB for the interest users and a variation of E_b/N_0 for the interfering users from 1 to 13 dB, resulting in a near-far ratio (NFR) in the range $[-6; 6]$ dB.

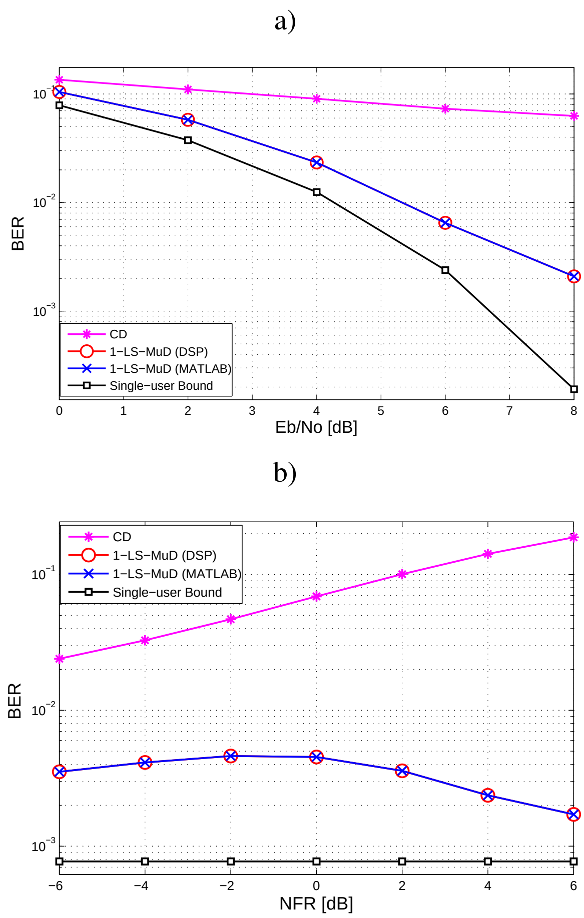


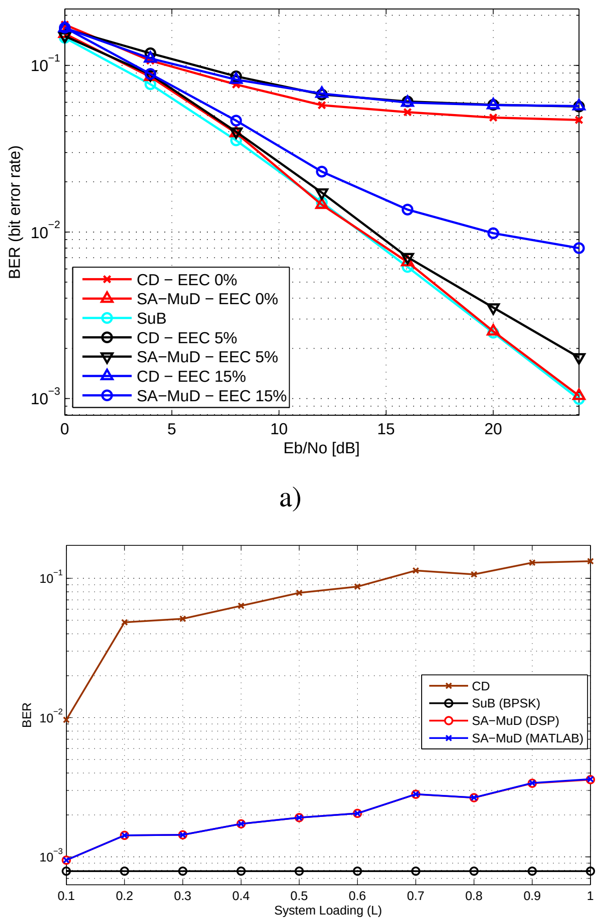
Figure 3: BER performance for 1-LS-MUD under AWGN channel. a) variation of $E_b/N_0[dB]$; b) Robustness to the near-far effect.

5.1.2 SA-MuD – Flat Rayleigh Channel

For the numerical performance results of the SA-MUD in MATLAB® the following parameters were adopted: Hamming distance equal to 1, initial temperature of SA, $T(0) = 3000$, the cooling constant $\epsilon = 0.1$, size series (Plateau) $L_{SA} = 1$. For the DSP implementation of the SA algorithm, the same parameters employed in the Matlab simulations was adopted.

It worth to note that the adopted parameter values for the SA algorithm were initially obtained from the literature and after additional and non-exhaustive optimization obtained via simulations, the final parameter values were obtained and employed in all SA-MuD simulations with results discussed herein.

Hence, in order to analyze the SA-MuD algorithm performance, the following operation system parameters was adopted: $N = 30$, $K = 10$, (low system loading $L = 0.333$). Thus, for this system loading, the BER of the SA-MUD in flat Rayleigh channel was obtained for perfect channel estimates, as well as for channel error estimates (EEC) of 5% and 15%, as shown in Figure 4.a.



a)

b)

Figure 4: BER Performance for the SA-MUD under flat Rayleigh channel. a) variation of E_b/N_0 with channel error estimates; b) Robustness to the system loading condition.

The system robustness to the multiple access interference (MAI) increasing was obtained. Hence, the performance degradation increment was induced by increasing the system loading as much as possible. The results presented in Figure 4.b assuming an $E_b/N_0 = 24dB$ suggests a relative robustness of the heuristic SA-MUD when the system loading increasing from 10% to 100%, been observed a little degradation in the BER performance by increasing of the system loading. However, the CD shows a dramatic degradation within this system loading range variation.

5.2 Complexity

In order to analyze the computational complexity of the LS-MUD and SA-MUD algorithms the number of cycles performed by the DSP were taken into account; the effective number of cycles computation were obtained through the CCS® Profile [13]. This tool allows to monitor simultaneously several parameters while the code (or part of it) is running on the DSP platform. Thus, we used the option "Cycles" of the CCS Profile which counts the number of cycles performed by the DSP when processing the code.

First of all, the complexity of the conventional detector (MFB followed by the abrupt decision) was determined, by performing various DSP processing cycles, taking into account different parameters values for the MuD, as the number of users K and the processing gain N. Thus, the average cycle values over five executions of the conventional detector were obtained, following the method employed in [11].

It is observed that the cycles carried out by the DSP during the execution of the CD function is proportional to K and N. Therefore, the complexity in terms of DSP cycles for the CD detector as a function of the proportionality factor KN, shows a linear behavior. As a result, eq. (9) presents the linearization fitting coefficients obtained for processing the CD cycles number under AWGN channel, while eq. (10) presents the linear fitting equation in terms of number of cycles for the CD receiver under flat Rayleigh channel.

$$DSP_{CD}^{\text{Cycles AWGN}} = \frac{1658 + (1120 \cdot K \cdot N)}{T_b} \quad (9)$$

$$DSP_{CD}^{\text{Cycles Rayl}} = \frac{3055 + (1133 \cdot K \cdot N)}{T_b} \quad (10)$$

where DSP_{CD}^{Cycles} is the number of processing cycles per second that the DSP executes for detecting a bit of all K users with processing gain N, in which the processing cycle must be completed within a period of detected information, T_b.

From the ML criterium, eq. (4), note that the terms $2\mathbf{y}^T\mathbf{C}^H\mathbf{A}$ and $\mathbf{CARAC}^H$ remain unchangeable within all iterations, regardless of candidate-vectors in any heuristic multiuser detection approach. Therefore, to reduce the computational complexity of Heur-MuD during the processing cycles in DSP, this terms were calculated separately outside of iterations loop, described by:

$$\mathcal{F}^{(1)} = Re\{2\mathbf{y}^T\mathbf{C}^H\mathbf{A}\} \tag{11}$$

$$\mathcal{F}^{(2)} = Re\{\mathbf{CARAC}^H\} \tag{12}$$

Hence, at each new iteration, only the new candidate-vector will be updated, and the ML criterium can be evaluated as:

$$\mathcal{F}(\vartheta) = \mathcal{F}^{(1)}\vartheta - \vartheta^T\mathcal{F}^{(2)}\vartheta \quad , \quad \vartheta = \text{candidate vector} \tag{13}$$

As proceed previously, different products $K \times N$ parameters were performed into DSP platform. Hence, in order to evaluate the number of cycles in DSP consumed with the Heur-MuD algorithms under AWGN channel and flat Rayleigh channel, the heuristic algorithms were divided into two parts, cycles carried out within Initial Cost Function and cycles of Iterations, getting the cycles average values in five executions of each function.

The DSP cycles associated with the Initial Cost Function were estimated analyzing only the processing performed before the iterations loop, i.e. calculations of the terms $\mathcal{F}^{(1)}$ and $\mathcal{F}^{(2)}$ followed by calculating the cost-function using the abrupt decisor. Furthermore, the DSP cycles of Iterations function were performed within the inner Heur-MuD loop until no improvement in the cost-function value for two consecutive iterations has been found.

Analyzing the data obtained it is observed that the two functions (Initial Cost Function and Iteration) implemented within LS-MuD and SA-MuD algorithms only depend on the number of users under both AWGN and flat Rayleigh channels, meaning the processing gain parameter (N) does not influence the cycles number computation for these two functions. This fact can be confirmed by checking that the processing gain does not affect the complexity of the algorithms, since the initial vector is given by vector on the abrupt decisor output obtained as a sign operation from MFB. As result, note that eq. (4) depends on the correlation between the spreading sequences.

Finally, *cubic polynomial* fitting was applied to estimate computational complexity of both Initial Cost and Iteration functions. The computational complexity for the HEUR-MUDS receivers is given by sum of the CD and heuristic algorithm cycles.

In addition, the percentage complexity increment ($CI_{\%}$) analysis was carried out, which is given by the ratio between the number of the HEUR-MUD receiver cycles and the CD detector cycles:

$$CI_{\%} = \frac{DSP^{\text{Cycles}}_{\text{Heur-MuD}}}{DSP^{\text{Cycles}}_{\text{CD}}} \cdot 100 \quad [\%] \tag{14}$$

For better analysis and comparison, also was established the percentage relative complexity analysis, given by:

$$RC_{\%} = \left(\frac{DSP^{\text{Cycles}}_{\text{SA-MuD}}}{DSP^{\text{Cycles}}_{\text{LS-MuD}}} - 1\right) \cdot 100 \quad [\%] \tag{15}$$

5.3 Receiver Complexity under AWGN Channels

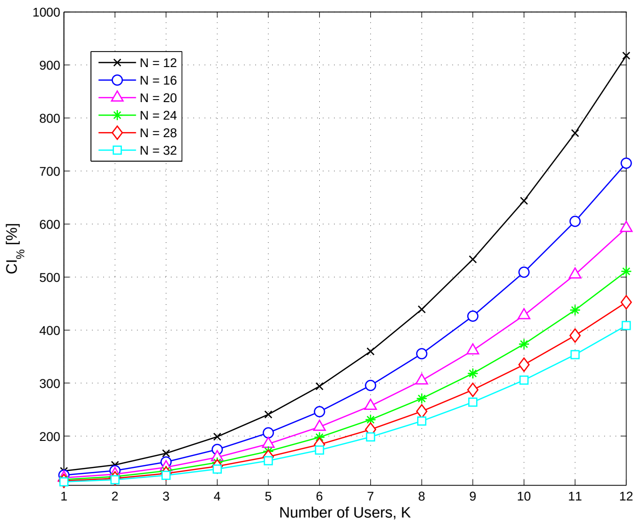
For AWGN channels, after applying polynomial fitting for heuristic functions and adding the CD detector complexity, the overall computational complexity for both analyzed HEUR-MUDS receivers is given, respectively, by:

$$\begin{aligned} DSP_{LS} = T_b^{-1} \cdot \big[1120KN + 26.5K^4 + \\ +364.2K^3 + 854.5K^2 + 2381.6K + 3202\big] \end{aligned} \tag{16}$$

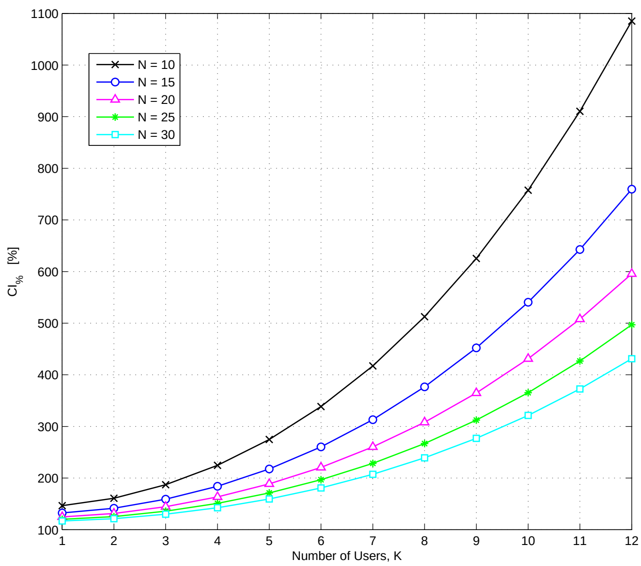
$$\begin{aligned} DSP_{SA} = T_b^{-1} \cdot \big[1120KN + 26.5K^4 + \\ +363K^3 + 865.3K^2 + 3121K + 3255\big] \end{aligned} \tag{17}$$

Note that the polynomial increasing of fourth order is determined by the users number. Figure 5 shows the percentage complexity increasing for both LS-MUD and SA-MUD receivers taking into account different processing gains in the range $N \in [10; 32]$. These complexities have the same behavior regarding the number of users K and processing gain N increasing, resulting in very close $CI_(\%)$ values for both detectors with same K and N. As expected, the complexity increases with the number of signals (i.e., K) processed simultaneously on the DSP platform. However, the complexity increasing over the conventional receiver (CD) presents a slowly increasing trend with the processing gain N, indicating that the processing cost per chip of spreading sequence decreases with the relative increase of N.

Figure 6 shows the percentage relative complexity of SA-MUD receiver regarding the LS-MUD receiver, as defined in eq. (15), for processing gain in the range $N \in [10, 30]$. One can observes that SA-MUD algorithm presents a small increase ($< 5\%$) in computational complexity for a wide range of processing gain and loading system, when compared to the DSP implementation of LS-MUD algorithm. Besides, this small increasing in complexity tends to decrease converging to the value $CR_{\%} \approx 0.5\%$ when the number of simultaneously processed user'signals, K, increases. At this asymptotic condition, the differences in processing gain N have little influence on the relative complexity. In summary, using the same design methodology, the DSP implementations for any type of heuristic detectors (particularly LS-MUD and SA-MUD algorithms), result in very similar complexities for practical system operation regions under AWGN channels.



a)



b)

Figure 5: Percentage complexity increasing $CI_{\%}$ for heuristics receivers: a) LS-MUD; b) SA-MUD.

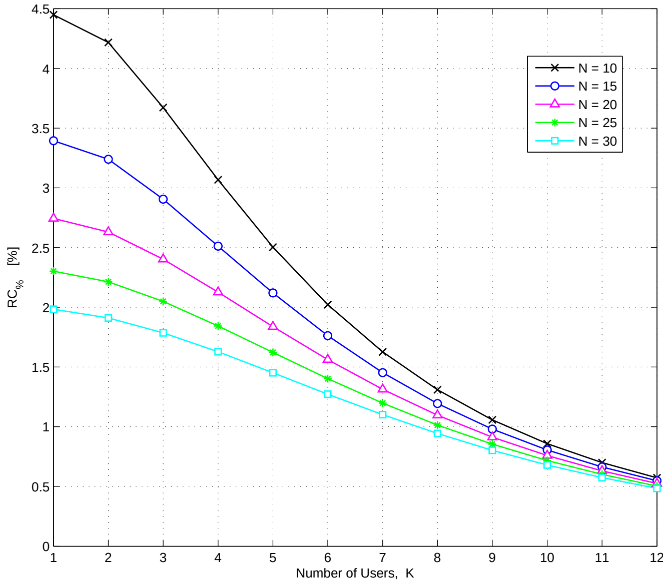


Figure 6: Relative percentage computational complexity of SA-MuD regards to LS-MuD as defined by (15).

5.4 Receiver Complexity under Flat Rayleigh Channels

For DS/CDMA system operating under flat Rayleigh channels, it was found that the computational complexity in terms of number of DSP cycles for both the LS-HEUR and SA-HEUR receivers is given, respectively, by:

$$DSP_{LS} = T_b^{-1} \cdot \big[1133KN + 26.5K^4 + \\ +596.7K^3 + 1254.8K^2 + 2577.1K + 4877\big] \quad (18)$$

$$DSP_{SA} = T_b^{-1} \cdot \big[1133KN + 27.34K^4 + \\ 584.6K^3 + 1238.5K^2 + 3736.5K + 4686\big] \quad (19)$$

As the channel becomes more degraded, i.e. from AWGN to flat Rayleigh channel, the impact on the heuristics receivers complexity relative to the conventional detector increases very marginally with the the increasing on the processing gain, as can be see from Figure 7. Hence, as found previously, the complexity also increases with the number of users, becomes of $\mathcal{O}(K^4)$ for flat Rayleigh channels.

Finally, Figure 8 shows the relative complexity percentage ($RC_{\%}$) as defined in eq. (15) when the number of users increases. Again, the same trend observed under AWGN channel for the asymptotic condition $K \to \infty$ was confirmed under flat Rayleigh channels.

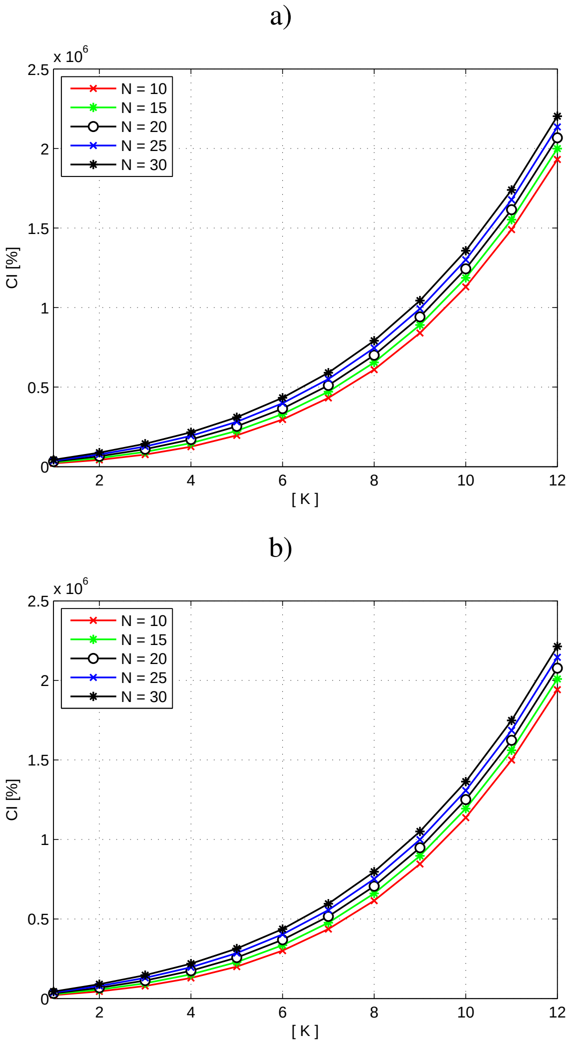


Figure 7: Graph of the complexity increase percentage $CI_{\%}$ to heuristics receivers: a) LS-MUD b) SA-MUD.

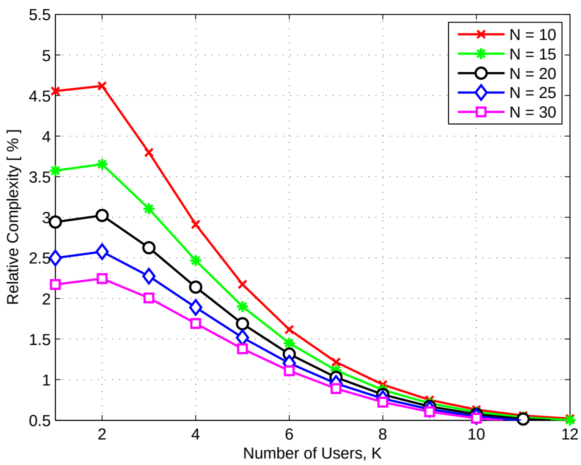


Figure 8: Computational Complexity comparison: LS-MuD × SA-MuD.

6 Conclusions

The heuristic local search and simulated annealing algorithms applied to the MuD detection problem under synchronous AWGN as well as Rayleigh Flat channels have been implemented and characterized in a *Texas TMS320C6713* DSP platform. The numerical results have shown that the obtained near-optimum performance allied to a reduced computational complexity when compared to the optimal ML detector makes the heuristic multiuser detection approach a suitable and promising technique with excelent performance-complexity tradeoff. The complexity reduction regarding the ML detector is provided by the reduced search space inherent to the heuristic approach.

Furthermore, two low-complexity near-optimum heuristic multiuser detector for baseband DS/CDMA system, based on LS and SA algorithms have been implemented on a commercial low cost DSP platform. Even considering real time applications both Heur-MuD implementations proved to be viable for practical system operation scenarios. As a result, exceptional performance improvements obtained with both Heur-MuD implementations with marginal complexity increasing over the conventional detector were reported.

Future work includes the implementation and characterization on DSP platform of HEUR-MUDS algorithms for single and multi-carriers systems equipped with multiple transmitted and received antennas subject to selective fading channels, mainly for non-line-of-sight wireless channel propagation, as well as the evaluation of the system performance degradation when errors occur in channel estimations.

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