

# Interactive Teaching of Multi-user Detection for DS-CDMA Systems using MATLAB\*

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*This paper describes a direct-sequence code-division multiple access (DS-CDMA) multi-user detection course and presents an interactive teaching method utilizing computers to demonstrate multi-user detection in DS-CDMA systems. The basic concepts related to the topic are presented using PowerPoint slides and reinforced by means of a series of MATLAB simulations. The computational techniques in evaluating the performance of multi-user detectors are also demonstrated using MATLAB. In particular, a DS-CDMA multi-user detection tutorial and simulator have been developed using MATLAB for teaching and self-study. While teaching the course it has been observed that the understanding of the students could be greatly enhanced by using simulations and interactive presentation skills.*

## INTRODUCTION

CODE-DIVISION MULTIPLE ACCESS (CDMA) is one of several methods of multiplexing wireless users. In CDMA, users are assigned unique codes rather than independent frequency bands, as in frequency-division multiple access (FDMA), or independent time slots, as in time-division multiple-access (TDMA). CDMA has been found to be attractive because of the characteristics such as potential capacity increases over other multiple access techniques, anti-multipath capabilities, soft capacity and soft handoff. Direct-sequence CDMA (DS-CDMA) is the most popular of CDMA techniques. DS-CDMA has been adopted as the multiple-access method for digital cellular voice communications in North America and standardized as IS-95 by the Telecommunications Industry Association (TIA) [1]. The third generation (3G) mobile radio service has generally accepted that CDMA is the preferred multiple access technique [2, 3].

Due to the problems of multiple-access interference (MAI), multi-user detection for DS-CDMA has received considerable attentions over the past 15 years. The utilization of multi-user detection has the potential to provide significant capacity improvement for DS-CDMA systems. DS-CDMA multi-user detection is one of the fastest growing areas in wireless communications. With the recent adoption of CDMA techniques in 3G systems, DS-CDMA with multi-user detection has become an important topic for students majoring in telecommunications. As a result, courses in DS-CDMA and multi-user detection are being

offered as part of the electrical engineering curriculum at the undergraduate and graduate levels.

Modern wireless communication systems based on CDMA techniques, such as the wideband CDMA (WCDMA) system [4], operate in environments that are interference, bandwidth, and multipath-fading limited. In order to combat these effects, complex receiver structures, such as those using complicated synchronization structures, demodulators and multi-user detectors, and RAKE processors, are often used. Many of these systems are not analytically tractable. The high complexity and the complicated performance analysis of the modern communication systems have become the major challenges in teaching the subject. Students are often unable to see or experience the phenomena being taught, and this problem often leads to an inability to learn basic principles and their practical relevance to implementation in real life. Furthermore, to ensure that analyses can be conducted analytically, complexity of the systems must be constrained. The constraints prohibit the study of more complex and more real-world systems.

The rapid advances in computer technologies revolutionize the teaching and analysis of the modern communication systems. With the incorporation of computers in the curriculum [5], it has become much easier to bring some of the concepts of this new and exciting field of wireless communications into the classroom. MATLAB (Mathworks, Inc., Natick, MA 01760–2098 USA) is being used extensively in colleges and universities to accomplish this integration of computers and curriculum. In this paper, a MATLAB-based approach is proposed and implemented to demonstrate the concepts of DS-CDMA and multi-user

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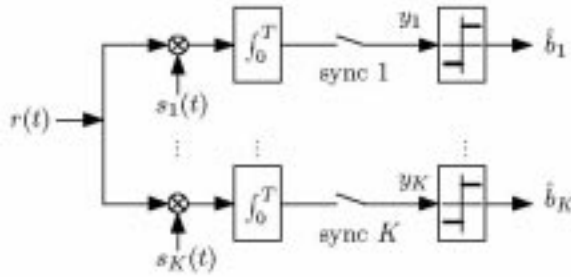


Fig. 1. Conventional (single-user) detector for DS-CDMA systems.

detection. We first review the basic theory and applications of DS-CDMA multi-user detection. We then focus on some MATLAB-based simulation learning tools that we have developed recently based on our experience of teaching an introductory course on DS-CDMA multi-user detection. The result is a learning tool that has proven to be extremely effective in presenting basic DS-CDMA and multi-user detection concepts. The key aim of the software is to bridge the gap between the theory and mathematics of textbooks and the practical applications and implementations of DS-CDMA multi-user detection.

### DS-CDMA MULTI-USER DETECTION COURSE

#### *Applications of multi-user detection in cdma systems*

In multiple access systems, CDMA communication techniques assign random and unique

signature codes to each of its users, which allow the transmission of signals overlapping both in time and frequency. The same codes are employed in receivers for demodulation of the users' signals. The capacities for the systems are no longer limited by the number of free time or frequency slots, but by MAI from other simultaneous users. The conventional detection approach is to pass the received signal  $r(t)$  through a bank of filters matched to the users' signature waveforms  $s_k(t)$ , and then decides on the information bits based on the sign of the output  $y_k$ , as shown in Fig. 1. Each user is detected separately considering the others as interference or noise. Due to MAI, the conventional detector often fails to produce reliable decisions.

The work of Verdu has shown that optimal near-far resistance and significant performance improvement over the conventional detector is achieved by an optimal maximum-likelihood multi-user detector [6, 7]. The substantial improvements, however, are obtained at the expense of a dramatic increase in computational complexity. When the number of users is large, it is desirable to use a simple but reliable suboptimum detector. Figure 2 shows several practical suboptimal multi-user detectors. The linear decorrelating detector [8] can significantly outperform the conventional detector at conditions where the MAI is dominant, without requiring knowledge of the user powers. It applies the inverse of the correlation matrix  $\mathbf{R}^{-1}$  to the matched filter output in order to decouple the received signal as shown in Fig. 2(a). To achieve better performance, we can turn the problem of linear multi-user detection into a problem of linear

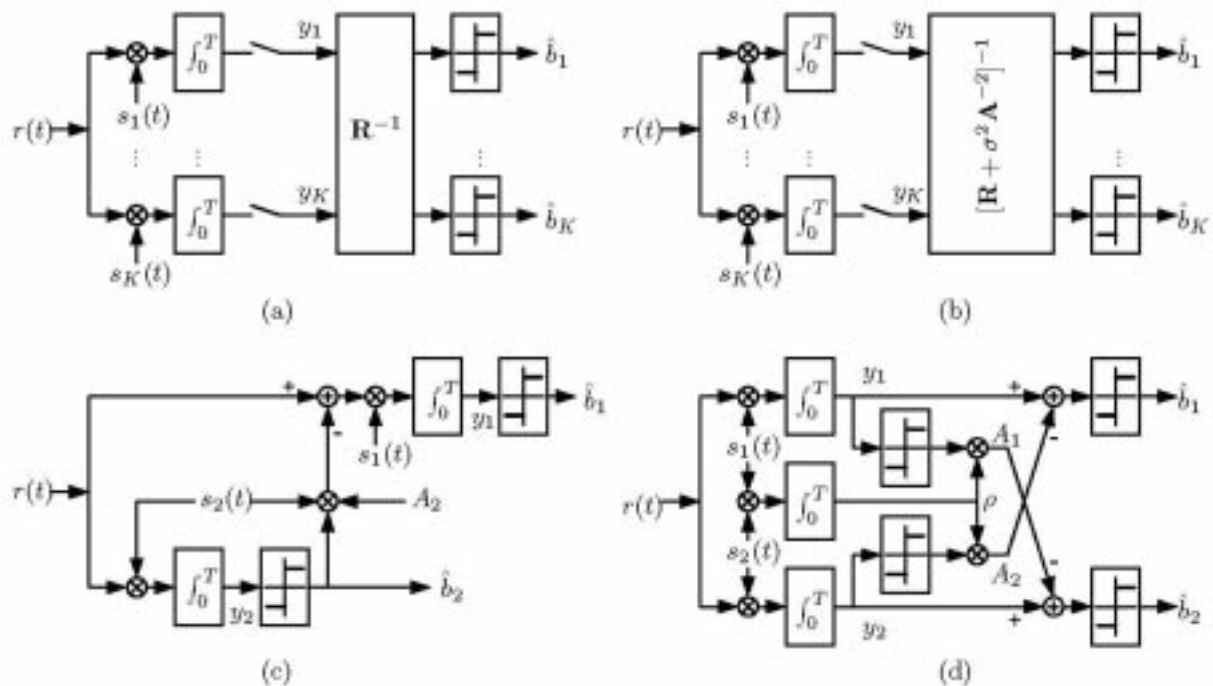


Fig. 2. Practical multi-user detectors for DS-CDMA systems: (a) decorrelating detector; (b) LMMSE detector; (c) two-user SIC detector; (d) two-user PIC detector.

estimation, by requiring that the mean square error between the  $k$ -user bit  $b_k$  and the output of the  $k$ th linear transformation of the matched filter outputs  $\mathbf{v}_k^T \mathbf{y}$  be minimized [9]. It is obvious that, the linear MMSE detector (Fig. 2(b)) replaces the transformation  $\mathbf{R}^{-1}$  of the decorrelating detector by  $[\mathbf{R} + \sigma^2 \mathbf{A}^{-2}]^{-1}$ . The LMMSE detector has the same asymptotic efficiency and near-far resistance as the decorrelating detector. Based on the numerical and analytical evidence, Poor and Verdu [10] conjectured that the bit error-rate of the MMSE detector is better than that of the decorrelating detector for all levels of background Gaussian noise, number of users and cross-correlation matrix.

The successive interference cancellation (SIC) takes a serial approach to canceling interference [9]. Each stage of this detector decides, regenerates and cancels out one interferer from the received signal, so that the remaining users see less MAI in the next stage. The SIC requires ordering of users according to their powers. The signal of stronger users are demodulated first and cancelled from the signals of weaker users. This technique provides an efficient and practical solution to the near-far problem. The two-user SIC detector is depicted in Fig. 2(c). The SIC detector requires only a minimal amount of additional hardware and has the potential to provide significant improvement over the conventional detector.

In contrast to the SIC detector, the parallel interference cancellation (PIC) detector (or multi-stage detector) estimates and subtracts out all of the MAI for each user in parallel [11]. It mitigates some of the shortcomings of the SIC techniques, e.g., the order in which users are cancelled greatly affects the performance of the SIC for a particular user. The PIC detector for two users is illustrated in Fig. 2(d). In the first stage, the conventional single-user matched filters bank is used, whereas in the second stage successive cancellation is performed simultaneously for both users. This process can be repeated to clean up the original matched filters output with, hopefully, increasingly reliable tentative decisions of the interfering users. When all the users are received with equal strength, the PIC outperforms the SIC. However, when the received signals are of distinctly different strengths (the more important case), the SIC is superior in performance. The important thing to note is that in both cases, both the SIC and PIC outperforms the conventional detector.

#### Course outline

The objective of the course is to present algorithms and architectures of linear and interference cancellation multi-user detectors as well as explain the computational simulation techniques that can be used to evaluate the performance of the multi-user detectors. As prerequisite, it is assumed that students have studied introductory probability, linear algebra and digital communications.

The syllabus of the course can be summarized as follows:

- Multi-access communications: the multi-access channels; FDMA and TDMA; random multi-access; CDMA.
- Code-division multiple-access channel: basic synchronous CDMA model; basic asynchronous CDMA model; signature waveforms; multipath fading; background noise.
- Single-user matched filter: optimal receiver for the single-user channels; the  $Q$ -function; performance of the matched filter in white Gaussian noise and Rayleigh fading.
- Optimum multi-user detection: optimum detector for synchronous channels; optimum detector for asynchronous channels; complexity.
- Linear multi-user detection: decorrelating detector; the decorrelating detector in the synchronous and asynchronous channels; performance analysis of the decorrelating detector; linear minimum mean-square error (LMMSE) multiusers' detection; performance analysis.
- Interference cancellation receivers: successive interference cancellation (SIC); performance analysis of the SIC; parallel interference cancellation (PIC); performance analysis of the PIC.
- Implementation of multi-user detectors: DSP implementation; VLSI implementation.

Students are referred to well-known texts and articles, e.g., [9, 12–14], for further background in multi-user detection; however none of the texts are compulsory purchases.

#### Course presentation and chronology

Students are first introduced to the principles of CDMA as well as the synchronous and asynchronous DS-SS channel models. Next, the simplest suboptimum detector, the conventional (single-user) detector as shown in Fig. 1, is described. The conventional detector has a complexity that grows linearly with the number of users. It is optimum when the signature sequences for any pair of users are orthogonal for all time offsets. However, it is not possible to design such signature sequences. As a result, the conventional detector is vulnerable to interference from other users and often fails when MAI is dominant.

Then, the optimum receiver, the receiver that selects the most probable sequence of bits given the received signal observed over certain time interval, is derived for both synchronous and asynchronous channels. From the results, it is apparent that the optimum detector has a complexity that grows exponentially with the number of users. This greatly motivates the requirement for a suboptimum detector that outperforms the conventional detector while having practical computational complexity.

By restricting the detector as a linear transformation of the matched filter-bank outputs, two simple yet reliable suboptimum multi-user

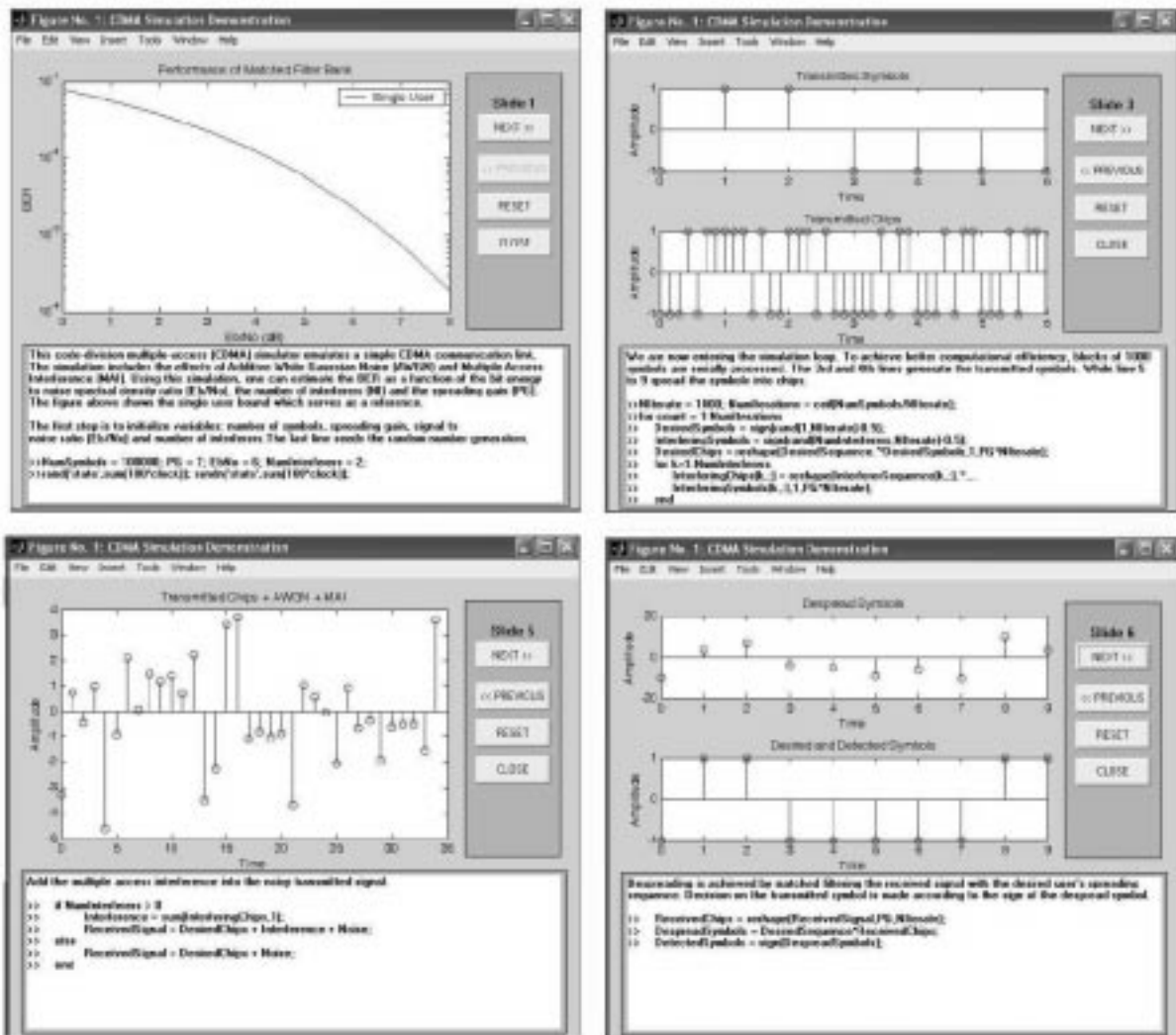


Fig. 3. The DS-CDMA simulation demonstration.

detectors, the decorrelating detector and LMMSE detector, can be easily derived by eliminating the interuser interference and minimizing the mean square error for each user signal, respectively. The students are then introduced to another multi-user detection technique called interference cancellation. The successive (serial) approach is first derived based on the idea that the interfering signals can be removed serially from the received signal. Then, the parallel technique that employs multiple iterations in detecting the user bits and canceling the interference is presented. The interference cancellation methods are best described by means of simple examples as depicted in Fig. 2(c) and (d).

During the teaching of the course, students are exposed to the computational simulation technique for DS-CDMA systems by using a MATLAB-based interactive tutorial. The tutorial prepares the students toward understanding the programming codes behind the multi-user detection simulator which is described in the next section. Based on our experiences, it has also greatly motivated the students to develop other

advanced multi-user detectors that can be evaluated in the simulator. The tutorial is briefly reviewed in Fig. 3.

The bit error probability is generally the desirable performance measure in multi-user communications. In evaluating the effect of multi-user interference on the performance of the detector for single user, we may use as a benchmark the probability of a bit error for a single-user receiver in the absence of other users of the channel. This single-user performance is shown in the upper left inset of Fig. 3. It is often used as a lower bound, since the probability of error for the optimum detector is extremely difficult and tedious to evaluate. Similarly, for the case of suboptimum multi-user detection, an analytical exact evaluation of bit error-rate is often difficult if not impossible. Therefore, in general, computational simulation appears to be inevitable. It is clear that the learning process would be greatly enhanced by a software tool that would allow the performance of the multi-user detectors to be evaluated by the student within just a few minutes of reasoned simulation. Hence the requirement for a software simulation tool is

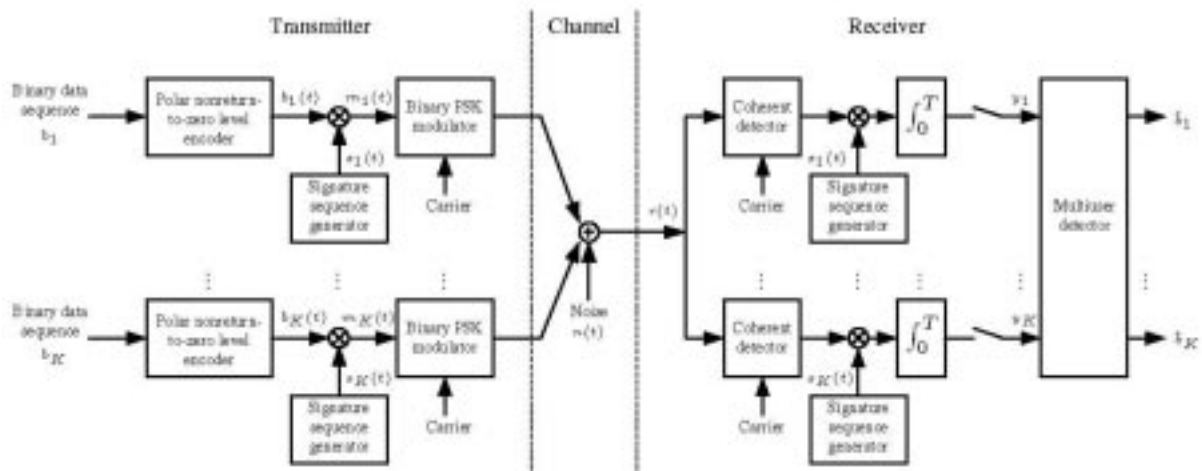


Fig. 4. The passband DS-CDMA system model.

clear. Unfortunately, no such learning tools were readily available.

### THE MULTI-USER DETECTION SIMULATOR

To demonstrate the way multi-user detectors perform and to give students an insight into how the different number of users, type of spreading sequences, spreading gains and signal-to-noise ratios affect the bit error-rate performance of the multi-user detectors, a multi-user detection simulator has been developed which compares five detectors in a DS-CDMA channel. Students are referred to well known texts, e.g., [15, 16], for further background on principles of communication systems simulation using MATLAB.

The internal setup of the demonstration and

teaching simulator is shown in Fig. 4. The data sequences  $b_k$  for all the users are independent and equally likely to be 0 or 1, while the observation noise signal  $n(t)$  is Gaussian white noise pseudo-random sequences. The data sequences and the white Gaussian noise can be generated using the MATLAB functions `rand` and `randn` respectively. The transmitter in Fig. 4 first converts the incoming binary data sequence  $b_k$  into a polar nonreturn-to-zero waveform, which is followed by two stages of modulation. The first stage consists of a product modulator or multiplier with the data waveform and the signature sequence as inputs. The second stage consists of a binary phase shift keying (BPSK) modulator.

The receiver consists of two stages of demodulation. In the first stage, the received signal  $r(t)$  and a locally generated carrier are applied to a coherent detector, i.e., a product modulator followed by a

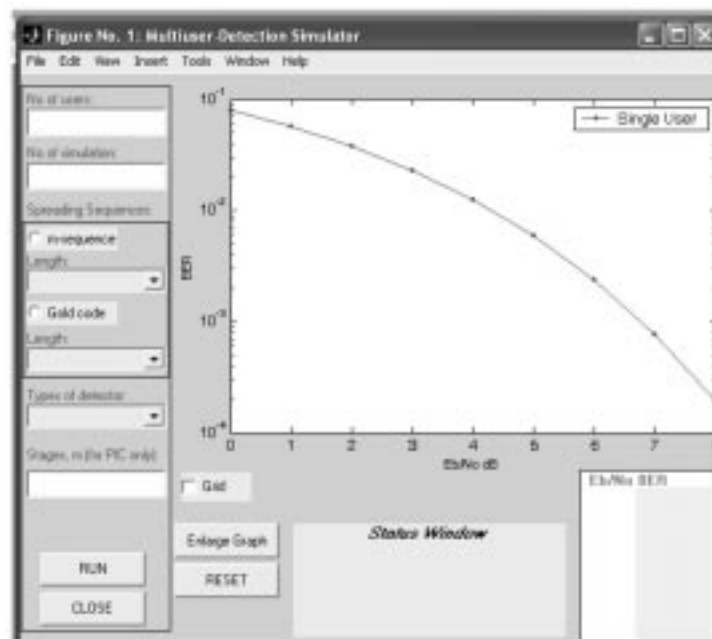


Fig. 5. The multi-user detection simulator.

low-pass filter whose bandwidth is equal to that of the original message signal  $m_k(t)$ . This stage of the demodulation process reverses the phase-shift keying applied to the transmitted signal. The second stage of demodulation performs spectrum despreading by multiplying the low-pass filter output by a locally generated replica of the signature sequences, followed by integration over a bit interval, and finally decision-making by using a multi-user detector.

The multi-user detection simulator is available for free at <http://www1.mmu.edu.my/~hslim>. The m-files for the simulator should be downloaded into a folder which is included in the paths of the MATLAB. In the command window, type in 'mud' and press Enter to start the simulator. A window, as shown in Fig. 5, is created which is the core element of the simulator. The window is partitioned into three parts.

On the left, the menus for setting the number of users, number of simulations, type and length of the signature sequences, and the type of multi-user detectors are given. For the type of signature sequences, two choices are provided where the students can select among maximal-length sequences (m-sequences) and Gold codes. For the type of detectors, students can select among conventional, decorrelating, LMMSE, SIC and PIC detectors. When using the PIC detector, the number of stages has to be specified.

After setting all the required parameters, the simulation can be started by clicking on the RUN button. A plot of bit error-rate (BER) versus bit energy-to-noise spectral density ratio ( $E_b/N_0$ ), at the upper right of the window, shows in real-time the results of the simulation. The performance of the selected multi-user detector is

determined for a range of  $E_b/N_0$  from 0 to 8 dB. At the bottom of the window, a Status Window that displays the current settings and status of the simulation, is shown next to the simulation output data. A RESET button is provided to clear the workspace and restore the original settings of the simulator. Some simulation results of the simulator are illustrated in Fig. 6.

Using this simulator, the system capacity, i.e., the largest possible number of users that can be reliably served by the system given a required BER, and various effects, such as changes on the type and length of the spreading sequences and the results on the multi-user detectors, can be observed and studied easily. Furthermore, the students can explore the performance of the detectors in increasing noise and MAI levels.

To assess the usefulness of the tutorial suite and the simulator, the author/lecturer administered a survey to the students of the DS-CDMA multi-user detection course. Overall results revealed that the majority of students found the tutorial suite and simulator useful and user friendly, with an overall rating of 4.50 out of 5. The questionnaire also posed three open-ended questions:

1. What were the best features of the software?
2. What were the worst features?
3. What improvements would you suggest?

The students' statement about the best features included that it was a good study aid and that the tutorials made it easy to understand the principles of DS-CDMA, and to design simulation models of DS-CDMA systems with different levels of complexity. Students also appreciated that performance of the system could be easily evaluated and visualized using the simulator.

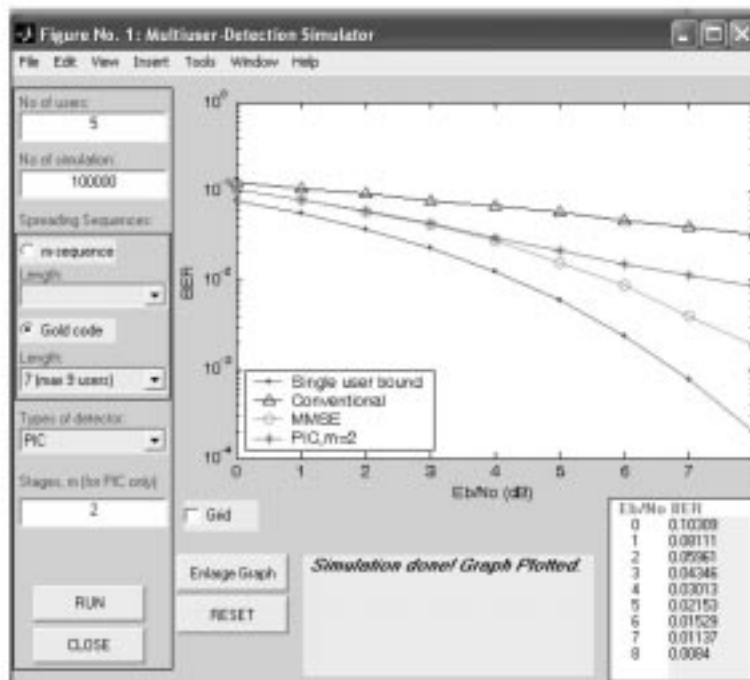


Fig. 6. The multi-user-detection simulator outputs.

Student statements on the worst features and suggested improvements were similar. Suggestions included adding an option for other modulation techniques, e.g., QPSK, QAM, etc., allowing for higher number of users, adding an option for other types of spreading codes, and making improvements in the style and wording on various tutorials.

## CONCLUSIONS

In this paper, we have described a DS-CDMA multi-user detection course offered to practicing engineers and graduate-level students at the Multimedia University. While teaching the course it has been observed that the understanding of the students could be greatly enhanced by using simulation and interactive presentation techniques. Therefore a MATLAB-based tutorial has been developed to demonstrate the computational simulation techniques for a basic DS-CDMA system using conventional detector. A MATLAB-based multi-user detection simulator is also developed to visualize the intricacies and to study the relationship between the different parameters involved in

multi-user detection. Some of these ideas have also been implemented in a course on Wireless Communications being offered at the undergraduate level. Students derive a number of benefits from the course. Through the use of simulation, students can study the operating characteristics of systems that are more complex and more real world than those studied in traditional DS-CDMA with multi-user detection courses since, in traditional courses, complexity must be constrained to ensure that analyses can be conducted.

Simulation allows system parameters to be easily changed, and the impact of these changes can be rapidly evaluated by using interactive and visual displays of simulation results. In addition, an understanding of simulation techniques supports the research programs of many graduate students working in the communications area. For the current simulator, a rather simple additive white Gaussian noise channel is considered in the simulations. Therefore, our current work is extending our ideas towards a more advanced tutorial and simulator that include the multipath fading effects.

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