Mansoura Engineering Journal, (MEJ), Vol. 31, No. 4, December 2006.

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Performance of Multistage Detectors in Synchronous CDMA Mobile Communication System

تقييم أداء الكواشف متعددة المراحل في النظام المتزامن في التقسيم الكودي متعدد الدخول لنظام الاتصالات الجوال

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ملخص البحث

الكاشف متعدد المستخدمين هو أساس تحقيق إمكانيات النظام الكودي متعدد الدخول و الذي أصبح أكثر انتشارا في أنظمة الاتصالات اللاسلكية المستقبلية. إن علاج مشكلة التداخلات بين نظام الكاشف متعدد الدخول (MAI) يعتبر موضوع حيوي في النظام الكودي متعدد الدخول.

يوجد نوعيات مختلفه من الكواشف متعددة المستخدمين تم اقتراحها للتقليل من مشكلة التداخلات بين المستخدمين و أبسطهم نوعا هو الكاشف ذو المستخدم الواحد (single user) و المستخدم فيه مرشح من نوع خاص حيث يهمل وجود التداخلات بين المستخدمين مع المستخدم المراد استقباله و يعتبر أداؤه غير مرضي بالإضافة إلى وجود مشكله في استقبال المستخدمين لاختلاف مستوى الإشاره الخاصة أكل منهم بين القريب و البعيد عن محطة الاستقبال (Near-Far-Problem).

هذه المقالة تعرض عدد من الكواشف و التي منها ما يحقق تحسين في أداء نظام الاستقبال بالإضافة إلى حل مشكلة اختلاف مستوى الإشارة المرسله من كل مستخدم عند نظام الاستقبال.

Abstract- Multiuser detection (MUD) is central to the fulfillment of the capabilities of code-division-multiple access (CDMA), which is becoming the ubiquitous air-interface in future generation communication systems. The problem of multiple access interference (MAI) is vital for a CDMA system. A variety of MUD has been proposed to mitigate the MAI. The simplest one is the single-user matched filter approach, which totally ignores the existence of MAI. Its performance is not very satisfactory and is particularly limited by the near-far problem. This paper presents the performance of different types of detectors as well as a solution for the near-far-problem using the decorrelator detector type.

Key words- MUD, MAI, decorrelator, near-far-problem

I. Introduction

Code-division-multiple-access (CDMA) [1] is a multiplexing technique that enables multiple users to access a common channel simultaneously. In a CDMA system, each user is assigned a unique signature waveform. The binary antipodal (±1) information bits are modulated by the code waveforms before transmission [2]. The received signal at the base station is a linear superposition of the multiple copies of the signals transmitted by all users due to multipath effects, each path is multiplied by an arbitrary amplitude factor and delayed by an arbitrary delay amount [2].

One can combat multipath interference by multipath reception, whereby the different multipath arrivals are considered as independent receptions of the signal and are used to give beneficial time diversity; this technique is called RAKE receiver [3]. CDMA has superior performance over time division multiple access (TDMA) or frequency division multiple access (FDMA) in mobile communication systems [4]. Here, we consider the synchronous case, in which the bit sequences of all users are aligned in time. Since the modulated signal has a much wider bandwidth than that required for

simple point-to-point communications, a CDMA system is also referred to as spread spectrum system. There are three techniques to spread a signal. The first technique is the direct sequence in which digital data is directly coded at a much higher frequency. The second technique is the frequency hopping in which the signal is rapidly switched between different frequencies within the hopping bandwidth pseudo-randomly, and the receiver knows where to find the signal at any given time. The third technique is the time hopping in which the signal is transmitted in short bursts pseudo-randomly, and the receiver knows beforehand when to expect the burst. CDMA systems show significant advantages over analog and conventional TDMA systems, including increased capacity, enhanced privacy and security, and reduced effects of multipath fading. The performance of the conventional single user receiver is limited by the near-far effect and more generally by the multiple access interference [2]. Centralized power control can be used to somewhat eliminate the near-far effect but the error performance is still far from optimum as shown by Verdu [5]. The interference from other users is known as multiple access interference (MAI). For DSSS-based CDMA (DS-CDMA) system, MAI is the major factor limiting the performance and hence, the capacity of the system. Multiuser receivers suppress the interference between users in spread-spectrum CDMA systems by making use of the structure of the multiple-access interference [5], [6] and of the knowledge of the code sequences. There are two classes of MUDs, linear and nonlinear. Linear MUD is more attractive than nonlinear ones because of their reduced complexity [4]. The decorrelator detector is a type of MUD used for its better performance than the conventional one. This detector is a mathematically straightforward linear MUD that usually outperforms conventional single-user CDMA receivers. The decorrelator

detector can completely eliminate multiple access interference (MAI) at the cost of enhanced background noise [7]. Near-far resistance and independence to received amplitudes are among other attractive features of the decorrelator. In addition to the noise enhancement the main drawback of this kind of linear detector is its computational complexity that is related to the matrix inversion and its updates. Another type of nonlinear detectors is the subtractive interference cancellation detector which depends on estimating the transmitted sequence of each user by the conventional matched filter, and then the strongest sequence is subtracted from the received waveform, resulting in a clean signal from interference of the strongest interferers [3].

There are many reasons for researchers to concentrate on MUDs, such as the enhancement of multiuser efficiency, capacity and resistance to the near-far-problem. It is very essential to find an appropriate solution for the near-far problem in CDMA systems by either using an elaborate power control scheme or developing some types of detectors which are not sensitive for the user's power, and so can reduce system complexity. To keep the system performance and capacity over fading channels as good as it should be, power control rate should be one hundred times higher than the maximum fading rate [8]. However, the class of MUDs considered in the following sections will alleviate the need for using power control. We'll investigate first the optimum MUD, then analyze the different types of suboptimum detectors.

As we know, the environment of CDMA mobile propagation suffers of different impairments which cause fading. There are two major categories of fading; long term fading which concerns with the changes in signal level due to slow variations in the propagation mechanism; and short term fading, which concerns with the simultaneously occurring modes of propagation or multipath [9]. On the other

hand, different code lengths are used in order to minimize mutual interference in DS-CDMA and the spreading codes with low cross-correlation should be chosen [10]. In our case study we use synchronous DS-CDMA with Gold code having low cross correlation for all users.

The contributions of this paper are twofold. First, we concentrate on the performance simulation of different types of detectors namely, conventional and decorrelator as well as the two stage with deccorelator first stage. The second contribution is to demonstrate the efficiency of such MUDs in solving the near-far problem instead of using power control schemes which lead to higher system complexity and cost. In section II, we introduce the CDMA system model, optimum detector, different types of linear detectors (Conventional, Decorrelator), and then multistage detector with first stage decorrelator. Section III presents the results. Finally, section IV summarizes the conclusion.

II. CDMA System Model

The general CDMA channel model is illustrated in Fig.1. In the reverse link of a CDMA system, the user data is first passed to the spreading stage where it is multiplied by the signature code which identifies each user, then modulated and transmitted to the base station. The channel has different impairments such as Rayleigh fading and AWGN. The receiver at the base station passes the multi-user signal to a bank of matched filters and reverses the operation of the transmitter (despreading) by multiplying the signal with the corresponding user signature code. In the following we introduce a brief discussion of different types of detectors which relate .to the paper's contribution.
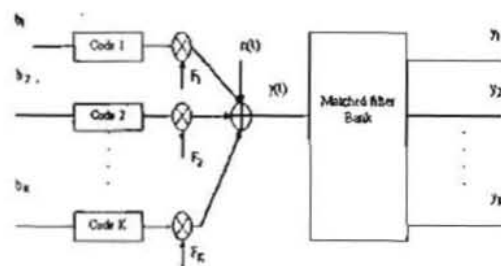

Figure 1. CDMA Channel Model

1. Optimum Detector

Assuming K-user direct sequence CDMA system transmitted using DPSK modulation with each transmitted signal selected from a binary alphabet and limited to $[0, T]$, where T is the symbol period. The kth user's transmitted signal is given by:

$$S_k(t) = \sum_{i=1}^{N} b_{k,i} C_k(t - iT) \qquad (1)$$

where $b_{k,i} \in \{+1, -1\}$ is the ith transmitted bit and $C_k(t)$ is the spreading waveform, and the parameter N denotes the number of bits being considered. The spreading code waveform, $C_k(t) = \sum_{n=0}^{N_c} C_{k,n} \prod(t - nT_c)$, is composed of N_c chips, where $C_{k,n} \in \{+1, -1\}$, $\prod(t)$ is the rectangular chip pulse waveform of duration T_c, and $T = N_c T_c$ is the symbol duration. In a typical system, all K- signals are transmitted simultaneously in a symbol synchronous fashion, so that the signal at the receiver denoted $r(t)$, can be written as follows [11]

$$r(t) = \sum_{i} \sum_{k=1}^{K} b_k^{(i)} C_k(t - iT) + n(t) \qquad (2)$$

In the above equation, $n(t)$ is the superimposed AWGN noise term and $b = [b_1, b_2, ..., b_k]^T$ is the K-tupel vector of the users data bits in the time interval $[0, T]$, i.e., considering $i = 0$. Assume the maximum likelihood (ML) decision on the users data vector is $\hat{b}^* = [\hat{b}_1^*, \hat{b}_2^* .... \hat{b}_k^*]^T$, which maximizes the log-likelihood function.

This ML decision can be written and analyzed in more detail as follows [12]:

$$\hat{b}^* = arg\left\{ \max_{b\in\{+1,-1\}^K} \left[2\int_0^T r(t)C(t,b) - \int_0^T C^2(t,b)dt \right] \right\} \quad (3)$$

where $C(t,b) = \sum_{K=1}^{K} b_K C_k(t)$. The optimum ML decision can be rewritten as [6]

$$\hat{b}^* = arg\left\{ \max_{b\in\{+1,-1\}^K} [2y^T b - b^T Hb] \right\} \quad (4)$$

where $y = [y_1, y_2, \ldots, y_K]^T$ is the vector of sufficient statistics with elements,

$$y_k = \int_0^T r(t)C_k(t)dt \text{ ,for } k = 1, 2 \ldots K \quad (5)$$

and $H = [h_{kl}]$ is the cross correlation matrix with elements given by,

$$h_{kl} = \int_0^T C_k(t)C_l(t)dt \quad (6)$$

There is a problem facing maximization in (3) that was mentioned in [6], and no algorithm can solve it in polynomial time if K is known. On the other hand, the complexity of (3) increases exponentially when number of users K exceeds 10 or 20 depending on the transmission rate [9], [11].

2. Linear Detectors

2.1 The Conventional Detector
The conventional detector is composed of a bank of K matched filters, a matrix filter, and a decision stage as shown in Fig. 2. Every user's code waveform is regenerated and multiplied by the received signal in a separate detector branch. This means that the conventional detector follows a single user strategy, so each branch detects the desired user's data without regard to the existence of other users. It is shown that the MAI in this detector is affected by the correlation properties of the users codes [3], and so the success of this detector depends on the choice of these codes. For these codes, it's desired to have an

autocorrelation much higher than the cross correlation between different codes [7].

The output of the conventional detector using the received signal of (2) is given by:

$$y_k = \frac{1}{T_b} \int_0^{T_b} r(t)C_k(t)dt$$

$$= b_k + \sum_{\substack{i=1 \\ i\neq k}}^{K} b_i h_{ki} + \frac{1}{T_b} \int_0^{T_b} n(t)C_k(t)dt$$

$$= b_k + MAI + \zeta_k \quad (7)$$

where $\zeta_k = \frac{1}{T_b} \int_0^{T_b} n(t)C_k(t)dt$

When taking the channel fading into account, the received signal (2) becomes:

$$r(t) = \sum_i \sum_{K=1}^{K} Wb_K^{(i)} C_k(t - iT) + n(t) \quad (8)$$

where W is a diagonal matrix of the multi-user Rayleigh fading channel coefficients; all having equal variances. So the sufficient statistics are given by

$$y_k = \frac{1}{T_b} \int_0^{T_b} r(t)C_k(t)dt$$

$$= Wb_k + \sum_{\substack{i=1 \\ i\neq k}}^{K} Wb_i h_{ki} + \frac{1}{T_b} \int_0^{T_b} n(t)C_k(t)dt$$
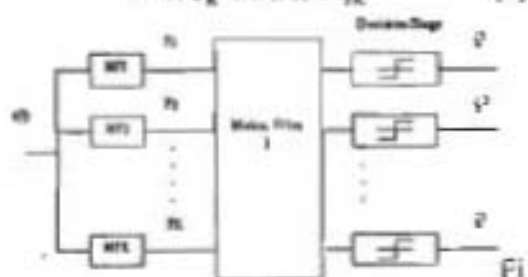
$$= Wb_k + MAI + \zeta_k \quad (9)$$

gure 2. Block Diagram of the Conventional Detector

2.2 The Decorrelator Detector
We noticed that in the conventional detector there were two main factors which cause the increase in BER, the MAI and AWGN terms. So, it's required to provide

an alternative method or technique to eliminate these factors. The decorrelator detector provides that solution for the MAI.

First, the vector of sufficient statistic $y = [y_1, y_2, \ldots, y_K]^T$ of all users shown in Fig.3 can be expressed as:

$$y = HWb + n \qquad (10)$$

where H, W are KxK matrices defined earlier and n is the Gaussian noise vector. Let us now suggest that the Gaussian noise does not exist, i.e. $n = 0$, and $y = HWb$. Then multiplying the sufficient statistics y by the inverse of H, the resulting equation will be $\bar{y} = H^{-1}y = Wb$. By adding the noise term back again, it's seen that the MAI is eliminated at the expense of increase in the noise term, such that:

$$\bar{y}^x = H^{-1}y^x = Wb^x + \hat{n}^x. \qquad (11)$$

As obvious in (11), using the decorrelator detector gives the ability to recover the transmitted signal without MAI effect, but on the contrary the noise floor will increase. It is seen that the decorrelator detector has many advantages over conventional type; its performance is independent of the powers of interfering users, so there is no need for pre-knowledge of user's power [3]. In addition, when user's energies are not known and the objective is to optimize the performance for the worst case MAI scenario, the decorrelator detector is the optimal approach [3], [6].
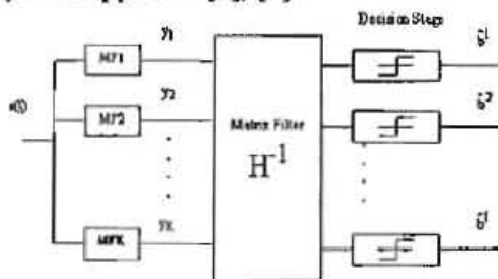

Figure 3. Block Diagram of the Decorrelator Detector

3. Multistage Detectors

Another important class of suboptimum detectors can be classified as subtractive interference cancellation detectors [12].

The basic principle underlying these detectors is the calculation at the receiver of separate estimates of the MAI contributed by other users in order to subtract out some or all of the MAI seen by each user. Such detectors are often implemented using multiple stages and are referred to as decision-feedback detector [13], where it is expected that the decisions will improve at the output of successive stages. These detectors are similar to feedback equalizers [3] used to combat inter-symbol-interference (ISI). In feedback equalization, decisions on previously detected symbols are fed back in order to cancel part of the ISI. This paper concentrates on a two-stage detector with decorrelator first stage.

We propose the multistage detector as a suboptimum alternative to the optimum detector. The key idea is the following. Suppose that the estimates of the vector b at the mth decorrelator stage is denoted as,

$$\hat{b}(m) = [\hat{b}_1(m), \hat{b}_2(m), \ldots \ldots \hat{b}_K(m)]^T$$

The $(m+1)^{th}$ stage estimate of the kth user's information bit b_k can be obtained using (4) for $m \geq 1$. It is easily shown that:

$$\hat{b}_k(m+1) = \text{sgn} [z_k(m)] \qquad (12)$$

where, $z_k(m)$ is the mth stage statistic for the kth user given by:

$$z_k(m) = y_k - \sum_{j \neq k} \hat{b}_j(m) \, h_{jk} \qquad (13)$$

In demodulating the information bits of all users, the maximization of (4) is performed for each of the K users. The $(m+1)^{th}$ stage estimates of b can then be written as the sign of the mth stage vector of decision statistics

$$Z(m) = [z_1(m), z_2(m), \ldots \ldots, z_K(m)]^T$$ so that:

$$\begin{aligned} \hat{b}(m+1) &= \text{sgn} [Z(m)] \\ &= \text{sgn} [y - (H - E) \hat{b}(m)] \end{aligned} \qquad (14)$$

where $E = diag(E_1, E_2, \ldots, E_K)$ is a diagonal matrix of the energies of the modulating signals as affected by the channel fading coefficients. From the definition of the sufficient statistic vector given in (10), it is easily shown that:

$$y = HWb + n$$
$$= Eb + I(b) + n \quad (15)$$

where the matrix W is lumped into E, and n is a zero-mean Gaussian noise vector with a covariance matrix $\sigma^2 H$ and $I(b) = (H - E) b$ represents the multiple-access interference vector. Substituting (15) into (12), the $(m+1)^{th}$ stage estimate of b is given by:

$$\hat{b}(m+1) = sgn[Z(m)]$$
$$= sgn[Eb + I(b) - I(\hat{b}(m)) + n] \quad (16)$$

The above result has a simple interpretation. The $(m+1)^{th}$ stage estimate of b is obtained as the sign of the mth stage statistics which in turn is obtained by subtracting the mth stage MAI estimate from the sufficient statistic y.

3.1 Two Stage with Decorrelator First Stage Detector

The block diagram of a two-stage detector with decorrelator first stage is illustrated in Fig. 4. The K bit estimates vector is obtained from the decorrelator first stage output which is denoted by $[\hat{b}_1(1), \hat{b}_2(1), \ldots, \hat{b}_K(1)]$. The second stage processes the (K-1) estimates of the interfering symbols to perform new multiple-access interference. Subtracting the sum of these multiple-access interferences from the sufficient statistic element of user 1 of the decorrelator first stage, we obtain the sufficient statistic element of the two-stage detector denoted by $z_1(2)$ given, according to (13), by:

$$z_1(2) = y_1 - \sum_{j=2}^{K} h_{1j} \hat{b}_j(1) \quad (17)$$

where (K-1) users ($j = 2, 3, \ldots, K$) interfere with the desired user 1. Decision is made by comparing $z_1(2)$ to a threshold so that the bit estimate of the second stage for user 1 is obtained as:

$$\hat{b}_1(2) = sgn[z_1(2)] = \begin{cases} 1 & if \quad z_1(2) \geq 0 \\ -1 & if \quad z_1(2) < 0 \end{cases} \quad (18)$$
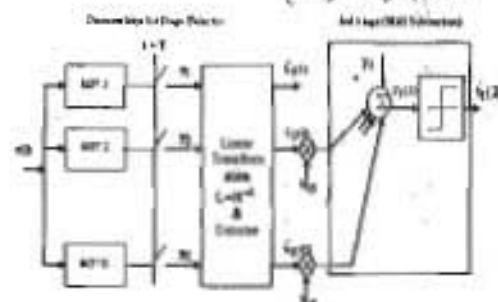

Figure 4. Two-Stage with first Stage Decorrelator Detector

III. Results

This paper presents the performance of different types of detectors subject to the following parameters, code length N_c, number of users K, and power ratios between the desired and interfering users. Results are obtained using MATLAB program ver.7. The sequence of the program starts with the generation of data, and Gold codes are used for spreading and despreading. The Gold sequences have cross correlation $(-1/N_c)$ which decreases with the code length. The channel is corrupted with Rayleigh fading and AWGN at the receiver assuming that the fading is modeled as single path (flat fading);

The following results illustrate a comparison of the performances of the conventional (CONV), decorrelator (DEC), and two stage with first stage decorrelator detector (MDEC) as well as their immunity to the near-far problem. Fig.5 shows the performance of different types of detectors with $N_c = 31$, and K = 15, 30, it's seen that the two-stage with decorrelator first has better performance than the conventional and decorrelator detector.
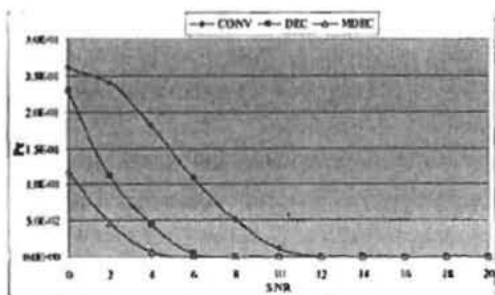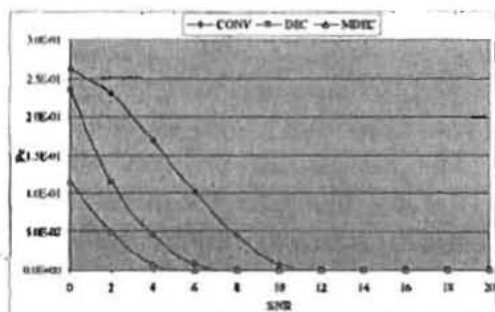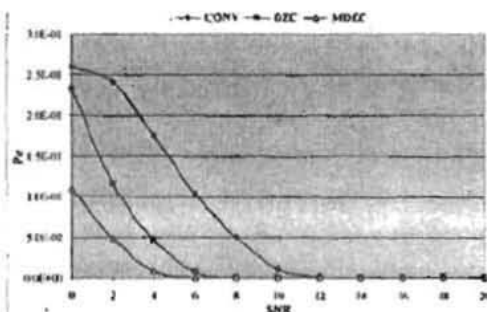
a. K = 15
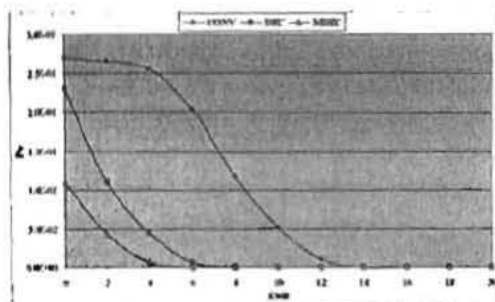
b. K= 30

Figure 5. Performance of Different Types
of Detectors with N_c = 31 and
K = 15, 30 ..

Comparing figure 6 for the
performance for he detectors with N_c = 63
and K = 15, 30 with the corresponding in
figure 5 for N_c = 31 and K = 15, 30, it is
indicated that the results of the
conventional detector gives better
performance when we increase the code
length. For the other detectors, we remark
that the performance insensitive for the
change of the code length.

a. K = 15

b. K= 30

Figure 6. Performance of Different Types
of Detectors with N_c = 63 and
K = 15, 30

Fig.7 shows that, the performance
degrades as number of users increases.
Fig.8 illustrates the performance of
different types of detectors as a function of
the power ratio between users under
detection (E_n / E_1), so the decorrelator and
two stage with first stage decorrelator have
steady performance as the SNRD is
increased (which means that they have
immunity to the near-far problem), in
addition to the better performance of the
two stage with decorrelator first stage than
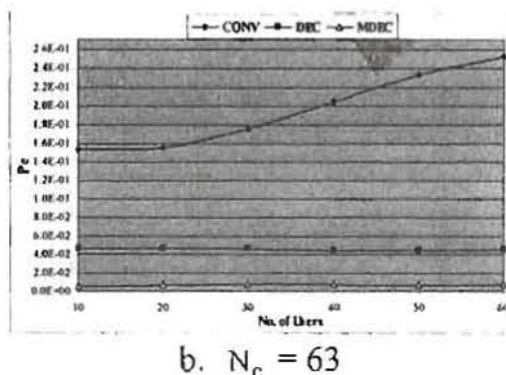the decorrelator detector.

a. N_c = 31

b. $N_c = 63$
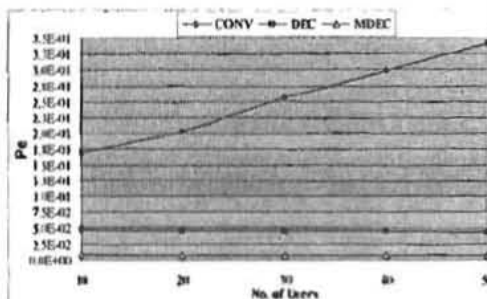
Figure 7. Performance of Different Types
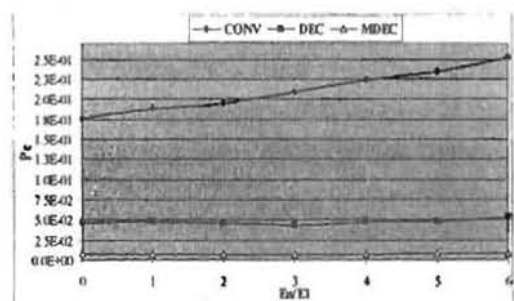of Detectors versus Number of Users,
$N_c = 31$, 63, and SNR = 4 dB

Figure 8. Performance of Different Types
of Detectors with Variable E_n / E_i for
$N_c = 63$, K = 30 and SNR = 4 dB

IV. Conclusion

As mentioned before, that the optimum receiver has a high computational complexity, so suboptimum detectors are proposed. Since the conventional detector ignores the MAI, the performance of the detector is degraded as shown in the results. From the results, we found that the decorrelator detector has a superior performance than the conventional one. Besides the decorrelator detector provides powerful treatment the problem of the near-far problem in mobile communication.

Another type of detectors is studied, the multistage detector. As shown in the results, the two-stage with decorrelator first stage has better performance than the decorrelator detector in addition to its immunity to the near-far-problem as well. Studying the effect of code length on the performance of detectors, it's shown that at high cross correlation between users, the conventional detector gives the worst results than decorrelator, which indicates the sensitivity of the conventional detector performance with the code length.

On the other hand, the effect of increasing the number of users is mainly equivalent to increasing SNRD between users, as shown in Figs.7, 8 as has been previously demonstrated [8].

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