

## MULTI-USER DETECTION TECHNIQUES FOR CDMA: A REVIEW OF BASIC PRINCIPLES

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### SUMMARY

*Multi-user detection (MUD) refers to the process of demodulating one or more user data streams from a non-orthogonal multiplex [18]. Here, the great work has been done especially for the development of receivers using MUD principle (so called MUD receivers) for the transmission systems based on code division multiple access (CDMA). The possibility of the development of optimum multi-user detectors providing maximum likelihood sequence detection [26] was the motivation for that work. The key algorithmic structure of the optimum MUD is that of a bank of matched filters (BMF) followed by a dynamic programming algorithm. The performance gain of the optimum MUD receiver is achieved by its centralized implementation involving a high degree of complexity. For practical systems, implementation complexity needs to be reduced to a reasonable level even if the performance is degraded from the optimum one. Following this idea, a number of suboptimum receivers have been studied over the past decade (e.g. [6,11,26,27]). In this paper, a short review of the basic principles of optimum and suboptimum MUD techniques is presented.*

**Keywords:** CDMA systems, MUD receivers, MAI, multiuser detection, suboptimum multiuser receivers

### 1. INTRODUCTION

The emerging third-generation (3G) wireless communications will support not only voice communications but also high-speed data and multimedia services. In addition, they will also allow subscribers to access several services at once. This means future wireless communications systems should provide a much higher capacity than current systems. Data and multimedia services also have a higher transmission quality requirement. For instance, data usually needs a bit error rate (BER) of better than  $10^{-6}$  as compared with a threshold  $BER=10^{-3}$  for voice. Higher capacity and higher quality requirements pose real challenge for designing of 3G wireless systems [27].

Although various solutions around the world have been proposed which reflect different requirements, there is one common envision that the wideband CDMA is the most promising technologies for the next-generations of wireless communications. In the CDMA, all users transmit simultaneously and at the same frequencies. The transmitted signals of all active users occupy the entire system bandwidth. Signature waveforms (code sequences, spreading codes) are used to separate one user from another. The CDMA provides a high spectral efficiency and a superior flexibility in the radio interface. It is well known that the capacity of the CDMA system is limited by multiple access interference (MAI), caused by non-orthogonality of signature waveforms of active users due to diverse phenomena such as asynchronous transmission, multipath propagation or limited bandwidth. Therefore, the MAI rejection is important to facilitate increased capacity in the licensed band that deploys CDMA. The techniques to mitigate the MAI in the CDMA can be divided into single-user detection and multi-user detection.

By single-user detection, we mean that one user's spreading code and delay is known and utilized at the receiver. The structure of the MAI (such as spreading codes, delays and powers of the other users) is assumed to be unknown. The complexity in single-user detection is generally much smaller than that of MUD. A short review of single-user detection schemes can be found e.g. in [6,11,26].

Much of the motivation for designing better multi-user detectors results from the theoretical capacity of Verdú's work [25] for optimum CDMA receivers. The optimum MUD requires for all CDMA users' spreading codes and delays to be known at the receivers. Then, they exploit the considerable structure of the MAI in order to increase the efficiency with which channel resources are employed. Because, the optimum MUD receiver is hopelessly complex, a number of suboptimal receivers have been proposed to approximate it, resulting in a large number of published papers.

In this paper, we will present a short overview of receivers based on various MUD techniques. In the next Section, a simple transmission model of CDMA system will be presented. The single-user and optimum MUD receiver will be defined in the Section 3 and 4, respectively. A short survey of the suboptimum multi-user receivers will be presented in the Section 5. In the conclusions, some topics for the further research concerning MUD will be indicated.

### 2. TRANSMISSION MODEL

In our paper we will work with the synchronous CDMA K-users base-band model, consisting of the sum of antipodally modulated signature waveforms embedded in additive white Gaussian noise (AWGN). Consider that the  $j$ -th user sends a stream

of bits  $\mathbf{b}_j = [b_j[-M], \dots, b_j[0], \dots, b_j[M]]^T$ . Then the signal at the input of the receiver can be expressed as

$$r(t) = \sum_{j=1}^K d_j(t) + \sigma n(t) \quad (1)$$

where

$$d_j(t) = A_j \sum_{i=-M}^M b_j[i] s_j(t - iT) \quad (2)$$

The notation introduced in (1) and (2) is defined as follows:  $A_j$  is the received amplitude of the  $j$ -th user,  $2M + 1$  is the data frame length,  $b_j[i] \in \{+1, -1\}$  is the  $i$ -th bit (symbol) sent by the  $j$ -th user,  $s_j(t)$  is the signature waveform assigned to the  $j$ -th user normalized so as to have unity energy,  $T$  is the inverse of the data rate,  $n(t)$  is additive white Gaussian noise with unit power spectral density (the noise power in the frequency band with  $B$  bandwidth is  $\sigma_n^2 = 2\sigma^2 B$ ). The signal  $d_j(t)$  is a part of  $r(t)$  originally transmitted by the  $j$ -th transmitter.

The signature waveforms  $s_j(t)$  can be expressed in the form

$$s_j(t) = \sum_{k=1}^N (-1)^{c_{jk}} p(t - (k-1)T_C) \quad (3)$$

In this expression,

$$p(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_C \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

is chip waveform with the chip interval  $T_C$  and  $N$  is the number of chips per bit.  $\{c_{jk}\}$  is a pseudorandom sequence of length  $N$ . The  $j$ -th pseudorandom sequence is applied for spreading of the information signal  $\mathbf{b}_j$  transmitted by the  $j$ -th user. Its element  $c_{jk}$  is assigned to the  $j$ -th user at the instant  $kT_C$ . As the pseudorandom sequences, Gold, Kasami or Walsh sequences can be used e.g. [6].

### 3. SINGLE-USER RECEIVERS

An approach of converting the input signal of the receiver into a discrete-time process is to pass it through the BMF (Fig.1). Each filter of the BMF is matched to the signature waveform of different user, i.e. the  $j$ -th matched filter (MF- $j$ ) is matched to the signature waveforms of the  $j$ -th user  $s_j(t)$ . Then the output of the MF- $j$  at the  $i$ -th data symbol is

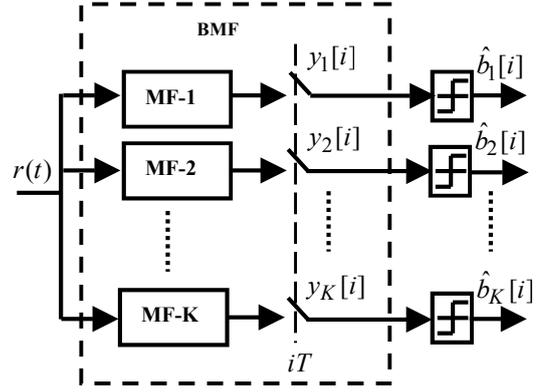


Fig. 1 Single-user receiver

$$\begin{aligned} y_j[i] &= y_j[iT] = \int_{iT}^{(i+1)T} r(t) s_j(t - iT) dt = \\ &= \sum_{m=1}^K A_m b_m[i] \rho_{jm} + n_j[i] = \\ &= A_j b_j[i] + \sum_{\substack{m=1 \\ m \neq j}}^K A_m b_m[i] \rho_{jm} + n_j[i] \end{aligned} \quad (5)$$

where

$$\rho_{mj} = \rho_{jm} = \int_{iT}^{(i+1)T} s_m(t - iT) s_j(t - iT) dt \quad (6)$$

$$n_j[i] = \sigma \int_{iT}^{(i+1)T} n(t) s_j(t - iT) dt \quad (7)$$

The equations (5)-(7) can be written for  $j=1, 2, \dots, K$ . It is convenient to express (5) in vector form:

$$\mathbf{y}[i] = \mathbf{R} \mathbf{A} \mathbf{b}[i] + \mathbf{n}[i] \quad (8)$$

where  $\mathbf{R}$  is normalized cross-correlation matrix of the signal set  $s_1(t), s_2(t), \dots, s_K(t)$  given by

$$\mathbf{R} = \begin{bmatrix} \rho_{11} & \rho_{12} & \dots & \rho_{1K} \\ \rho_{21} & \rho_{22} & \dots & \rho_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{K1} & \rho_{K2} & \dots & \rho_{KK} \end{bmatrix} \quad (9)$$

and

$$\mathbf{y}[i] = [y_1[i] \quad y_2[i] \quad \dots \quad y_K[i]]^T \quad (10)$$

$$\mathbf{b}[i] = [b_1[i] \quad b_2[i] \quad \dots \quad b_K[i]]^T \quad (11)$$

$$\mathbf{A} = \text{diag}(A_1 \quad A_2 \quad \dots \quad A_K) \quad (12)$$

$$\mathbf{n}[i] = [n_1[i] \quad n_2[i] \quad \dots \quad n_K[i]]^T \quad (13)$$

$\mathbf{n}[i]$  is zero-mean Gaussian random vector with covariance matrix equal to  $E[\mathbf{n}[i] \mathbf{n}^T[i]] = \sigma^2 \mathbf{R}$ .

The output of the single-user receiver (so called MF receiver) is given by

$$\hat{\mathbf{b}}[i] = \text{sign}(\mathbf{y}[i]) \quad (14)$$

where

$$\hat{\mathbf{b}}[i] = [\hat{b}_1[i] \ \hat{b}_2[i] \ \dots \ \hat{b}_K[i]]^T \quad (15)$$

and

$$\hat{b}_j[i] = \text{sign}(y_j[i]) \quad (16)$$

are the estimates of  $\mathbf{b}[i]$  and  $b_j[i]$ , respectively.

#### 4. OPTIMUM MUD RECEIVERS

The operation of the MF receiver may be viewed as the computation of the correlation of the received signal with a specific user signature sequence followed by a hard decision of the correlator output. For a system with orthogonal signatures, in the presence of AWGN, this receiver is optimum, whereby the criterion for optimality is minimization of the average symbol error. In a practical CDMA system, user signatures are non-orthogonal, causing MAI, which is essentially non-Gaussian. The MF receiver enhances the desired signal while suppressing other interfering signals viewed as Gaussian noise. Since the interfering signals are non-Gaussian, the performance of the conventional MF receiver is far from optimum [6,25].

As shows (5), the output of the MF consists of a term that is proportional to the transmitted symbol in that interval and the interference term computed as the sum of the cross-correlation of the signature for the user of interest and all other interferers. The interference term depends on the sequences of transmitted symbols for all interferers before and after the symbol of interest.

In the MF receiver, the decision device, which follows the MF, makes one-shot decisions. That is, it estimates the transmitted symbol on the basis of the received signal only in the interval corresponding to that symbol. In this approach, detection is also not optimum since the information on interference coming from overlapping symbols from other users is ignored. In optimum detection of CDMA signals, observation of the whole received waveform for all users at the output of the BMF is necessary. Therefore, for optimum demodulation we assume that the receiver has the information about the signature waveforms for each user as well as time delays, phase shifts and amplitudes of each user signal.

Optimum MUD receivers [6] could be designed to select the bit sequence

$$\hat{\mathbf{b}} = [\hat{\mathbf{b}}_1^T \ \hat{\mathbf{b}}_2^T \ \dots \ \hat{\mathbf{b}}_K^T]^T \quad (17)$$

which maximizes the conditional probability

$$P[\hat{\mathbf{b}} | r(t)] \quad t \in (-MT, MT + 2T) \quad (18)$$

The decision rule (18) results in the minimum sequence probability. Assuming that the transmitted bits are independent and equip probable, maximizing the probability (18) is equivalent to maximize the likelihood

$$\begin{aligned} P[r(t) | \hat{\mathbf{b}}] &= \\ &= C \exp \left\{ -\frac{1}{2\sigma_n^2} \int_0^T \left[ y_j(t) - \sum_{j=1}^K b_j(0) A_j s_j(t) \right]^2 dt \right\} \\ &\text{for } t \in \langle 0, T \rangle \end{aligned} \quad (19)$$

where  $C$  is a constant,  $\sigma_n^2$  is the noise power, and  $y_j(t)$  is the output of the MF-j. The optimization of (19) can be achieved by dynamic programming. The Viterbi algorithm is one example of a forward dynamic programming algorithm that selects  $\hat{\mathbf{b}}$  as to maximize the likelihood in (19). The inputs to the Viterbi algorithm are the samples of the BMF output. The Viterbi algorithm operates on a trellis with the number of states proportional to  $2^{K-1}$ . Therefore, the complexity of the algorithm is an exponential function of the number of users.

Optimum MUD receiver can make decisions by selecting the transmitted sequence to minimize the sequence error probability. This decision type is called maximum likelihood sequence detection [6]. The maximum likelihood detector for the CDMA consists of the BMF followed by the maximum likelihood decision Viterbi algorithm (Fig. 2).

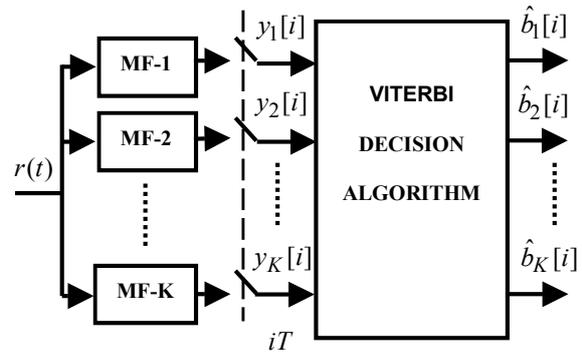


Fig. 2 Optimum MUD receiver for CDMA

#### 5. SUBOPTIMUM RECEIVERS

The performance gains of the optimum receiver are achieved by centralized implementation, which involves a high degree of complexity. For practical systems, implementation complexity needs to be reduced to a reasonable level even if the performance is degraded from the optimum one. Following this idea, a number of suboptimum receivers have been proposed. Most of these replace Viterbi decision algorithm with a reduced complexity algorithm. Some variations of receivers

of that kind include e.g. decorrelating MUD receivers (D-MUD), minimum mean square error linear MUD receivers (MMSE-MUD) and non-linear single-stage MUD receivers (NSS-MUD). Another suboptimum non-linear receivers use multi-stage interference cancellation (IC) to remove the interfering signals during detection. Excellent reviews of suboptimum MUD receivers can be found e.g. in [6,11,26,27]. In the next, a short survey of the basic principles of the suboptimum multi-user receiver operation will be presented.

### 5.1 Decorrelating receivers (D-MUD)

The output of D-MUD ( $\hat{\mathbf{b}}[i]$ ) is taken as the sign of the output of the BMF ( $\mathbf{y}[i]$ ) multiplied by the inverse cross-correlation matrix  $\mathbf{R}^{-1}$  [6,11,26]. The signals  $\hat{\mathbf{b}}[i]$ ,  $\mathbf{y}[i]$  and the matrix  $\mathbf{R}$  are defined by (8)-(13). Then, the output of D-MUD is given by

$$\hat{\mathbf{b}}[i] = \text{sign}(\mathbf{R}^{-1}\mathbf{y}[i]) = \text{sign}(\mathbf{A}\mathbf{b}[i] + \mathbf{R}^{-1}\mathbf{n}[i]) \quad (20)$$

The D-MUD is not only simple but it is optimum according to different criteria: least-squares and maximum likelihood when the received amplitudes are unknown [26]. The most significant feature of this receiver is its relatively low complexity compared to the optimum receiver. Another important attribute is that the receiver does not require knowledge of the received amplitudes, making it near-far resistant. However, the receiver needs the information on the signature waveforms, carrier phases, and timing of all the users.

In the literature, a lot of modifications of the basic principle of the D-MUD have been described [4,6,15-17,20,26]. The applications and the performance properties of the particular the D-MUD modifications depend especially on the channel properties. The following modifications of the D-MUD can be given as example:

- the D-MUD including the concept of penrose's generalized inverse of a matrix called Pseudo-decorrelator with the application for a Rayleigh fading multipath channel [17],
- the D-MUD with diversity reception based on RAKE architecture [4],
- the adaptive D-MUD and multi-rate D-MUD [15],
- the optimum finite precision D-MUD [16],
- the D-MUD for dual rate CDMA systems [20].

### 5.2 Linear MMSE receivers (MMSE-MUD)

The output of the MMSE-MUD ( $\hat{\mathbf{b}}[i]$ ) is taken as the sign of the linear transformation of the output of the BMF ( $\mathbf{y}[i]$ ) [6,11,14,26]. The signal  $\mathbf{y}[i]$  is defined by (5)-(10). Then, the output of MMSE-MUD is given by

$$\hat{\mathbf{b}}[i] = \text{sign}(\mathbf{M}\mathbf{y}[i]) \quad (21)$$

where transformation matrix  $\mathbf{M}$  is selected in such a way as to minimize  $E\left[\|\mathbf{b}[i] - \mathbf{M}\mathbf{y}[i]\|^2\right]$ . It can be shown (e.g. [26]), that  $\mathbf{M}$  satisfying this condition can be found in the form

$$\mathbf{M} = \left[\mathbf{R} + \sigma^2\mathbf{A}^{-2}\right]^{-1} \quad (22)$$

where  $\mathbf{R}$ ,  $\mathbf{A}$  and  $\sigma^2$  have been defined in the Sections 2 and 3.

From the practical point of view, it is desirable to obtain a MMSE-MUD that would not only eliminate the need for on-line computation of its transformation matrix  $\mathbf{M}$ , but it would also eliminate the need to know the cross-correlation matrix  $\mathbf{R}$ , or in general, the signature of the interfering users. This problem can be solved by the application of the adaptive form of MMSE-MUD [1,6,13,14,26,28] based on adaptive filter theory (e.g. [7]).

The adaptive MMSE receiver consists of an adaptive fractionally spaced adaptive digital filter followed by a decision device. It does not require signature waveform, timing, and carrier phase information about the all interferers, but only the timing and carrier phase of the desired user. A training sequence is used to estimate the initial filter parameters. In the training mode, the transmitter generates a data symbol sequence known to the receiver. This sequence is used to establish synchronization and to estimate filter parameters. In the transmission mode, the adaptation of the receiver is decision directed [9]. This means that the receiver decisions are used instead of the training signal to adjust the filter coefficients.

In the single-user equalization and identification literature, adaptive algorithms that operate without knowledge of the channel input (i.e. without training sequences) are called blind. In spite of the fact, that the blind detectors are based on the minimum output energy criterion (minimum output variance), it has been shown (e.g. [26]) that they converge to the MMSE-MUD. Therefore, the blind MMSE-MUD can be considered to be a special form of the adaptive MMSE-MUDs. This type of detector only needs to know the signature sequence, timing offset, and carrier phase of desired users.

In the literature concerning MMSE-MUD, a number of papers can be found. Besides adaptive and blind MMSE-MUD [2], the following modifications of the MUD are discussed in this field:

- the improved MMSE-MUD (so called IMMSE-MUD) based on asymptotic multi-user efficiency and Bayesian approach and equipped with a new updating mechanism for adapting receiver parameters to a dynamic character of the transmission channel [5],
- the single-bit single-user MMSE-MUD with the reduction of the length of the impulse response of the adaptive filter [21],

- the blind joint multi-user detection and channel equalization for CDMA system with multipath channels [12].

### 5.3 Non-linear single-stage receivers (NSS-MUD)

The theoretical analysis of a decision boundary in the CDMA has been shown that the optimum decision boundary is nonlinear [26]. The optimum receiver approximates this non-linear boundary perfectly, however, this can be achieved at the expense of computational complexity. On the other hand, the NSS-MUD can approximate this non-linear boundary well and outperform linear receiver structures [22]. The NSS-MUD techniques include adaptive decision feedback filter receiver (DF), neural network receiver and Volterra receiver.

The DF principle [9] uses an adaptive filter to suppress interference. Decisions are made at the output of the filter and then fed back to train the adaptive filter to be included in the filtering process. Because within feedback a threshold operation is applied, the DF belongs to non-linear receiver. In [3], decorrelating DF detector for synchronous CDMA has been described. The complexity of the DF is linear in the number of users, and it requires only one decision per user. Performance gains with respect to the linear D-MUD are more significant for relatively weak users, and the error probability of the weakest user approaches the single-user bound, as interferers grow stronger. Another interesting modification of DF receiver has been described e.g. in [19]. In this receiver, the final decision is taken based on the feed forward estimates and the previous and current decisions of the interfering user's data. It has been shown in [19], that the proposed DF

receiver modification can be applied with success in the AWGN and Rayleigh fading channel.

The MUD based on neural networks or Volterra processor have been proposed e.g. in [22,23], respectively. Here, the basic principle consists in a non-linear transformation ( $NT(\cdot)$ ) of the BMF output. From the view of the signal processing theory, the nonlinear transformation given by neural network can be understood as a multi-input and multi-output neural network. On the other hand, the nonlinear transformation due to a Volterra processor can be described as multi-channel (or multi-input and multi-output) Volterra filtering. With regard to these facts, the output of the NSS-MUD ( $\hat{\mathbf{b}}[i]$ ) is taken as the sign of the non-linear transformation of the output of the BMF ( $\mathbf{y}[i]$ ). The signal  $\mathbf{y}[i]$  is defined by (5)-(10). Then, the output of the NSS-MUD is given by

$$\hat{\mathbf{b}}[i] = \text{sign}(NF(\mathbf{y}[i])) = \text{sign}(NF(\mathbf{R}\mathbf{A}\mathbf{b}[i] + \mathbf{n}[i])) \quad (23)$$

The parameters of the neural network or the Volterra processor applied in the NSS-MUD are selected usually in such a way as to minimize

$$E\left[\|\mathbf{b}[i] - \hat{\mathbf{b}}[i]\|^2\right].$$

The non-linear transformation represented by the neural network or the Volterra processor is applied with intention to approximate the highly complex optimal receiver much more better than in the case of a linear MMSE receiver. The results presented in [22,23] have confirmed the fact that the NSS-MUD outperforms linear the MMSE-MUD.

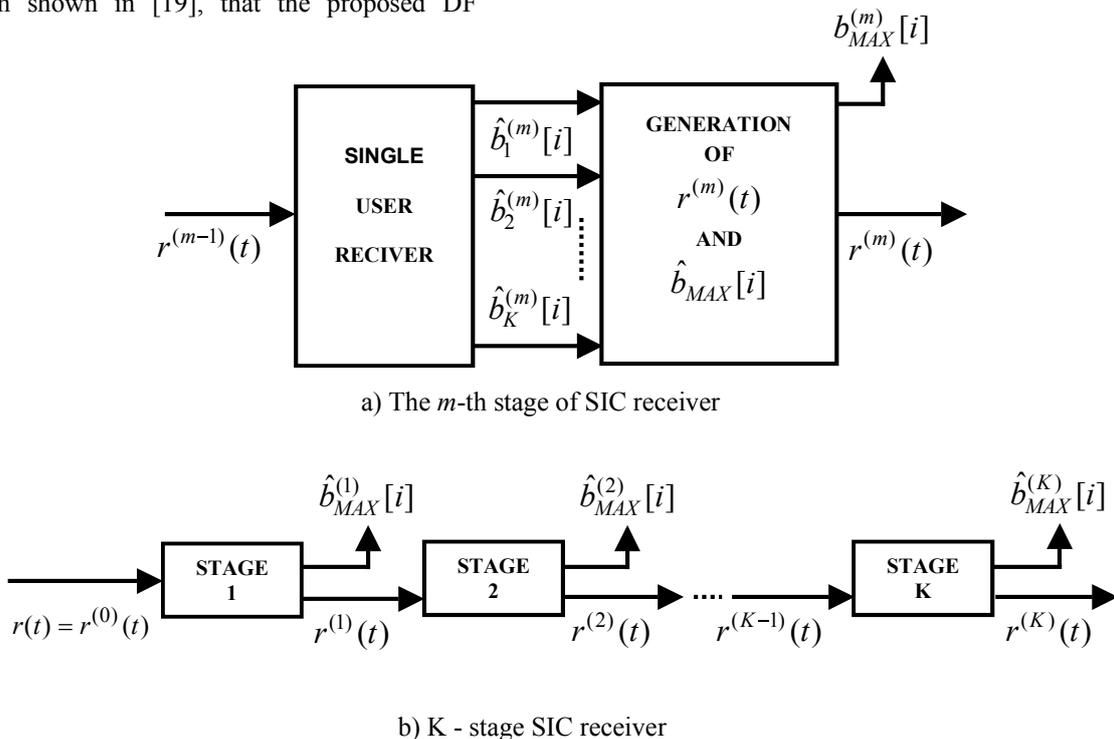


Fig. 3 SIC receiver

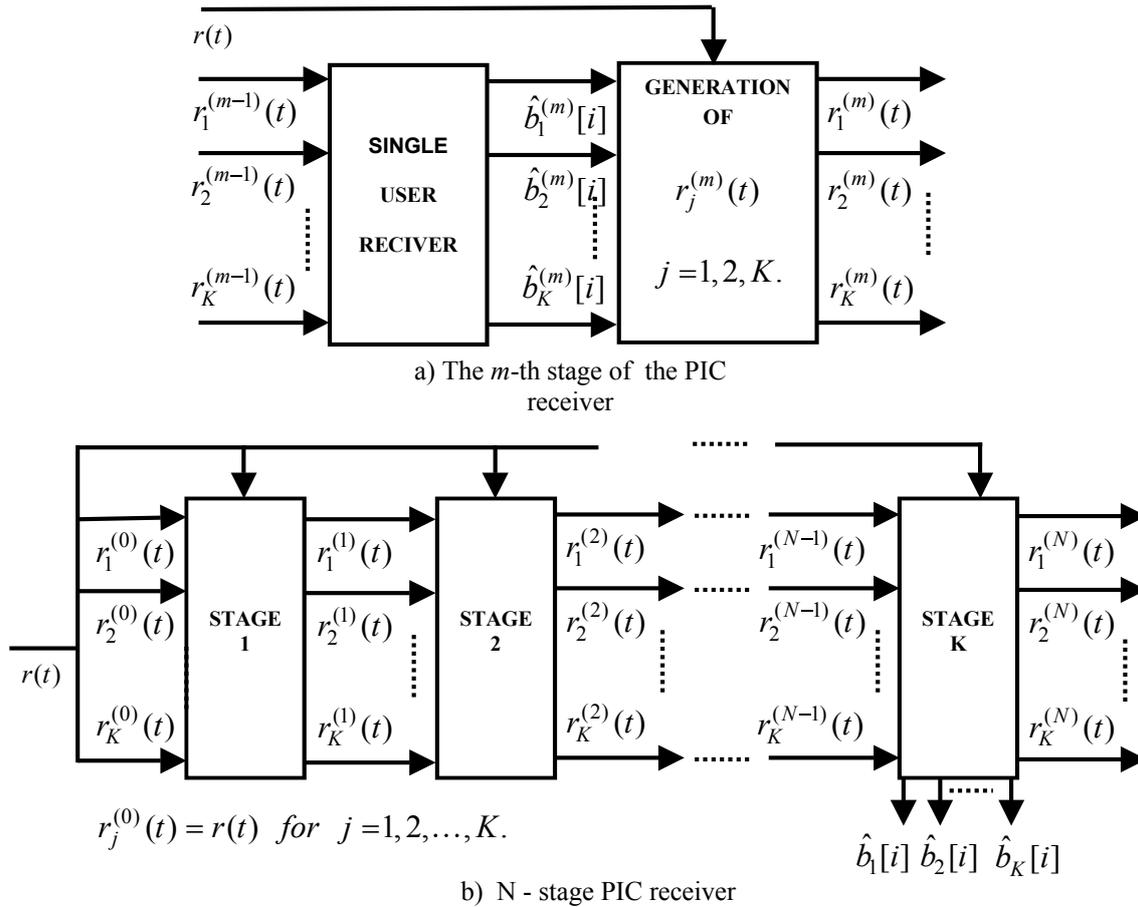


Fig. 4 PIC receiver

#### 5.4 Non-linear Multiple Stage Receivers

This kind of the suboptimum receivers uses the IC to remove the interfering signals during detection. In an IC scheme, the signal is first passed through the BMF and then each user's signal  $d_j(t)$  is reconstructed and cancelled from the received signal. This process may be repeated for multiple stages. The IC effectiveness is a function of the quality of the estimation and reconstruction. The IC performance is tied to the signal parameters and whether they are known. In the case of the IC, the signature waveforms, timing, and phases of all users must be known. Several implementations of the IC exist, but the most important are successive IC (SIC) and the parallel IC (PIC) [11,27].

The SIC receiver scheme is shown in Fig. 3. At each stage of the SIC receiver, all user's signals  $d_j(t)$  are estimated. The signal with the largest power is then regenerated and subtracted from the buffered received signal. Let, the signal with the largest power in the  $m$ -th stage is  $d_j(t)$ . Then, the regenerated form of the received signal in the  $m$ -th stage is given by

$$r^{(m)}(t) = r^{(m-1)}(t) - \hat{d}_j(t) \quad (24)$$

The signal  $d_j(t)$  reconstructed at the  $m$ -th stage of the SIC receiver is given by

$$\hat{d}_j(t) = \hat{A}_j^{(m)} \sum_{i=-M}^M \hat{b}_j^{(m)}[i] s_j(t-iT) \quad (25)$$

where  $\hat{A}_j^{(m)}$  is the estimate of  $A_j$  and  $\hat{b}_{MAX}^{(m)}[i] = \hat{b}_j^{(m)}[i]$  is the estimate  $b_j[i]$  at the  $m$ -th stage of the SIC receiver. In the next stages, the process will continue until all the users' signals have been recovered or the maximum allowable number of cancellation is reached. In the case of the receiver for  $K$ -users, the SIC receiver will usually contain  $K$  stages.

The SIC has been shown to be very robust to imperfect power control in the CDMA system. The SIC is considered to be one of the simplest forms of the IC because of the single-stage cancellation. However, the processor performing the cancellation must perform all cancellations while maintaining the necessary data.

In the field of the SIC a number of modifications of the basic principle can be found. E.g. in [10], the adaptive version of the SIC based on LMS algorithm has been described. On the other hand, the SIC equipped with a co-channel interference cancellation detector has been proposed in [8].

The basic base-band model of the  $N$ -stages PIC receiver proposed by Varanasi and Aazhang [24] is given in the Fig. 4. The  $m$ -th stage of the PIC receiver contains the BMF that is used to generate the estimate of the  $k$ -th user's signal  $\hat{b}_k^{(m)}[i]$ . The BMF outputs are also used for a reconstruction of the signals  $d_k(t)$ . The signals  $d_k(t)$  reconstructed at the  $m$ -th stage of the PIC receiver are given by

$$d_k^{(m)}(t) = \hat{A}_k^{(m)} \sum_{i=-M}^M \hat{b}_k^{(m)}[i] s_k(t-iT) \quad (26)$$

where  $\hat{A}_k^{(m)}$  is the estimate of  $A_k$  at the  $m$ -th stage of the PIC receiver. In the next stage, a new estimate for the  $k$ -th user is formed by taking the received signal and subtracting from it all reconstructed signals  $d_j^{(m)}(t)$  for  $j=1, \dots, K$  and  $j \neq k$ . Consequently, the reconstructed received (input) signal at the stage  $m+1$  for the  $k$ -th user is

$$r_k^{(m)}(t) = r(t) - \sum_{\substack{j=1 \\ j \neq k}}^K d_j^{(m)}(t) \quad (27)$$

The process may be repeated for an arbitrary numbers of stages. Then, the estimate of  $b_k[i]$  provided by the  $K$  stages PIC receiver is given by

$$\hat{b}_k[i] = \hat{b}_k^{(K)}[i] \quad (28)$$

It was shown that the three or four stages represent a practical complexity for the PIC receiver to provide the meaningful results. The number of operations for PIC is greater than for the SIC. Individual processors may be used for receiving and regenerating users' signals when compared to the single processor that must be used for successive SIC.

## CONCLUSIONS

In order to prepare this review, we went through a number of papers concerning the MUD theory. Because of the limited range of this paper, not all of these sources could be discussed and given in the references. With regard to the state of art of the MUD theory and applications, the following basic conclusions as well as topics for the next research concerning the MUD could be presented:

a) The MUD can eliminate MAI caused by other active users in the CDMA. Verdú has shown in [25] that the optimum detector provides a performance that approaches single-user bound. In other words, the optimal detector performs as if other users were not exists. Therefore, the

MUD is very important candidate for the 3G CDMA receivers.

- b) The optimum MUD receiver is too complex. Therefore, the research in this field has been intent on development of the suboptimal receivers. The suboptimal receiver should possess better performance properties (especially BER) than that based on a simple BMF, however at the lower complexity than that of the optimum receiver.
- c) Very attractive forms of the suboptimal receivers are the adaptive and blind MMSE-MUD, non-traditional NSS-MUDs, the SIC and PIC receivers and their combinations, as well as the receivers working in multi-rate environment or in variable spreading factor environment, the MUD receivers for the multi-carrier CDMA, etc.
- d) The additional topics for the research concerning the MUD receivers are e.g. impact of power control on the MUD performance, MUD receiver implementation, MUD and narrowband interference cancellation, performance properties of suboptimum receivers under condition that a transmission channel is multipath and fading, combination of convolutional coding with interference cancellation, etc.

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