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Low Complexity Selective Adaptive Multicarrier DS-CDMA Receiver

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Abstrak

Paper ini menampilkan sebuah penerima adaptif selektif (selective adaptive (SA) receiver), untuk sistem Multicarrier Direct Sequence Code Division Multiple Access (MC DS-CDMA). Penerima ini memiliki performa yang tinggi dan sekaligus mengurangi multiple access interference (MAI) pada sistem MC DS-CDMA dengan tingkat kompleksitas komputasi yang rendah. Kinerja SA receiver diukur pada aspek bit error rate (BER). Suatu persamaan batas atas untuk BER pada SA receiver di bawah kondisi Rayleigh fading channel diturunkan dan divalidasi dengan simulasi komputer. Selanjutnya, tingkat kompleksitas implementasi dari SA receiver dibandingkan dengan tingkat kompleksitas implementasi Adaptive Parallel Interference Cancellation (APIC) receiver.

Kata kunci: *sistem komunikasi multicarrier, sistem spektrum tersebar, fading channel*

Abstract

In this paper, selective adaptive (SA) receiver for Multicarrier Direct Sequence Code Division Multiple Access (MC DS-CDMA) system is presented. This receiver has high performance and at the same time reduces the multiple access interference (MAI) of the MC DS-CDMA) system with low computational complexity. The performance of SA receiver is measured in terms of the bit error rate (BER). An upper bound expression of the BER for the SA receiver under Rayleigh fading channel condition is derived and validated by computer simulations. Moreover, the implementation complexities of the SA receiver is compared with the Adaptive Parallel Interference Cancellation (APIC) receiver.

Keywords: *multicarrier communication systems, spread spectrum systems, fading channel*

1. Introduction

Multi-carrier direct-sequence code division multiple access (MC-DS-CDMA) and Interleave division multiple access (IDMA) inherits all the advantages of CDMA with the capability to overcome its deficiencies, and is one of the strong competitors for next generation wireless networks [1][2][3]. One of the problems of MC-DS-CDMA systems is the multiple access interference (MAI) which reduces the capacity of these systems [4]. Many multiuser Detectors (MUD) algorithms have been proposed in the literature to eliminate the MAI [5]. There are two main varieties of interference cancellation schemes, Serial Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) [6]. PIC can be classified into two categories, linear PIC (LPIC), and non Linear PIC. Under assumption of perfect channel estimation, the non Linear PIC outperforms the LPIC. An extension to PIC, called partial parallel interference cancellation (PPIC), has been proposed in [7]. In this scheme, it has been shown that if interference is removed partially at each stage, the performance of the system would be significantly better than complete cancellation. One problem of this approach is that the computational complexity is high in time-varying environments. Also, when the required statistics are not properly estimated, the performance may be seriously affected. To remedy the problem, an adaptive approach using the Least Mean Square (LMS) algorithm was then proposed for partial PICs [8]. There are many advantages using the adaptive PIC [9]. It is inherently applicable in time-varying environments. Also, it does not have to conduct robust channel estimation, and its performance is better than non adaptive. As in [10], the adaptive multistage PIC was applied to multi-rate systems. S-PIC and SA-PIC schemes were introduced

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with CDMA in [11] and [12] respectively. The performance of these schemes were evaluated with computer simulation, it has been found that both schemes have good performances in terms of bit error rate (BER), with low implementation complexity relative to conventional PIC and APIC. An upper bound of the BER of S-PIC scheme in a typical DS-CDMA communication system has been introduced [13].

For MC DS-CDMA many of MUD schemes have been developed to mitigate degradation of its performance as MAI increased [14]-[15]. One of the most promising schemes is the APIC scheme which was introduced for MC DS-CDMA in [16]. The major drawback of this system is its complexity, since weights are needed to be calculated for all sub-carriers and users of the system.

According to this literature review [17], the use of SA-PIC with MC DS-CDMA has not been studied before. In this paper, the SA-PIC is applied to MC DS-CDMA and the performance of MC DS-CDMA using SA-PIC is studied and analyzed. Moreover, an upper bound expression of the BER for the SA-PIC under Rayleigh fading channel condition is derived. Finally the implementation complexities for SA-PIC and APIC are discussed and compared.

The rest of this paper is organized as follows. In Section 2, the MC DS-CDMA system is introduced. In Sections 3, selective adaptive parallel interference cancellation is presented. Simulation results are shown in Section 4 including the evaluation of the complexity of the reduced complexity receiver. Finally, conclusions are presented in Section 5.

2. MC DS-CDMA System Model

The block diagram of the orthogonal MC DS-CDMA transmitter of user k is shown in Figure. 1. In this scheme the initial data stream having the bit duration of T_b is Serial to Parallel converted to p number of lower-rate sub streams, hence the new bit duration after the s/p conversion or the symbol duration is $T_s = p\ T_b$. Each of the p lower-rate sub streams is spread by the time-domain spreading code $c^k(t)$, which is a purely random PN code. Each of the p sub streams is transmitted by M number of subcarriers, in order to achieve a frequency diversity of order M at the receiver by combining these subcarrier signals with the aid of certain types of combining scheme. Hence, the total number of subcarriers required by the orthogonal MC DS-CDMA system is $U = pM$. Based on this, the transmitted signal of user k can be modeled as equation (1).

$$\mathrm{s}_k(t) = \sum_{i=1}^{P}\sum_{j=1}^{M}\sqrt{\frac{2p_k}{M}}\,b_i^{(k)}(t)c^{(k)}(t)\cos(2\text{®}f_{ij}t + \text{¤}_{ij}^{k}), \qquad (1)$$

where P_k is the transmitted power of the kth user, $b_i^{(k)}(t) = \sum_{n=-\infty}^{\infty} b_i^k[n]P_{T_s}(t - nT_s)$,where i= 1, 2, ….., P represents the binary data of the ith sub stream, $b_i^k[n]$ is assumed to be random variable taking value of ±1 with equal probability, while $P_{T_s}(t)$ represents the rectangular shape waveform, and $c^k(t)$ represents the T domain spreading code assigned to the user k, which is the same for all the $U = pM$ number of subcarriers. The spreading sequence $c^k(t)$ can be expressed as $c^k(t) = \sum_{\ell=-\infty}^{\infty} c_\ell^k P_{T_c}(t - \ell T_c)$, where c_ℓ^k assumes values of ±1, while P_{T_c} is the chip waveform of the T domain spreading sequence, which is defined over the interval [0, T_c), finally, ¤_{ij}^k represents the initial phase associated with the carrier modulation in the context of the subcarrier determined by (i,j) in (1).The channel is assumed to be a slow varying, frequency-selective Rayleigh fading channel with a delay spread of T_m . The principle motivation for using MC-CDMA is to allow a frequency selective fading channel to appear as flat fading on each subcarrier, assuming the number of subcarrier is sufficiently large [1]. With this assumption, each subcarrier experiences a complex flat-fading channel with transfer function for the subcarrier (i,j) of the user k can be defined as equation (2).

$$¸_{ij}^{(k)}(t) = \sim_{ij}^{k}(t)\exp[j \cdot {}_{ij}^{(k)}(t)], \qquad (2)$$

Where $\sim_{ij}^{k}(t)$ is a Rayleigh-distributed stochastic process with unit second moment, and $\cdot\,{}_{ij}^{(k)}(t)$ is uniformly distributed over $(0,2®]$. It is assumed that the channel transfer function $¸_{ij}^{(k)}(t)$ is independent and identically distributed (i.i.d.) for different values of k and (i,j). The system model is assumed to be a synchronous MC DS-CDMA system with BPSK modulation to considerably simplify the exposition and analysis. Synchronous systems are becoming more of practical interest since quasi-synchronous approach has been proposed for satellite and microcell applications [3][13].

Assuming that the system consists of K synchronous users, and the user of k=ii is the reference one. The proposed receiver block diagram of the reference user is shown in Figure 2. All users use the same $U = pM$ subcarriers, the average power received from each user at the base station is also assumed to be the same, implying perfect power control. When the transmitted signal is in the form of (1), the received signal at the base station can be expressed as equation 3.

$$r(t) = \sum_{k=1}^{K}\sum_{i=1}^{p}\sum_{j=1}^{M}\sqrt{\frac{2P}{M}}\sim_{ij}^{k} b_i^k(t) c_k(t)\cos(2®f_{ij}t + \ddot{}_{ij}^{\,k}) + n(t) \qquad (3)$$

Where $\ddot{}_{ij}^{\,k} = ¤_{ij}^{k} - \cdot\,{}_{ij}^{k}$, is assumed to be an i.i.d random variable having a uniform distribution in [0, 2®), $n(t)$ represents the AWGN with zero mean and double-sided PSD of variance $N_0/2$.

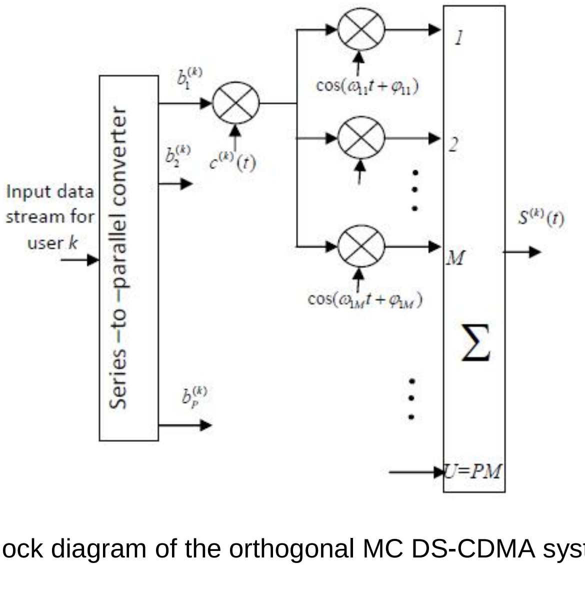

Figure1. Transmitter block diagram of the orthogonal MC DS-CDMA system for the kth user.

The receiver provides a coherent correlation for each subcarrier and the correlated outputs associated with the same data bit are combined to form a decision variable. Assuming that the receiver is capable of tracking the carrier phases of the subcarrier signals of the reference user, therefore, $\ddot{}_{ij}^{\,ii}$ is set = 0. The superscripts and subscripts concerning the reference user will be omitted for the sake of simplicity. For Maximal Ratio Combining (MRC) the decision variable for detecting bit u for the reference user b_u can be written as equation (4).

$$Z_u = \sum_{v=1}^{M} Z_{uv} = D_{uv} + N_{uv} + \sum_{\substack{k=1 \\ k \neq ii}}^{K} I_1^{(k)} \tag{4}$$

Where $Z_{uv} = \int_0^{T_s} r(t) g_{uv} c(t) \cos(2\pi f_{uv} t) dt$ .Giving that, $g_{uv} = \alpha_{uv}$ is assumed, associated

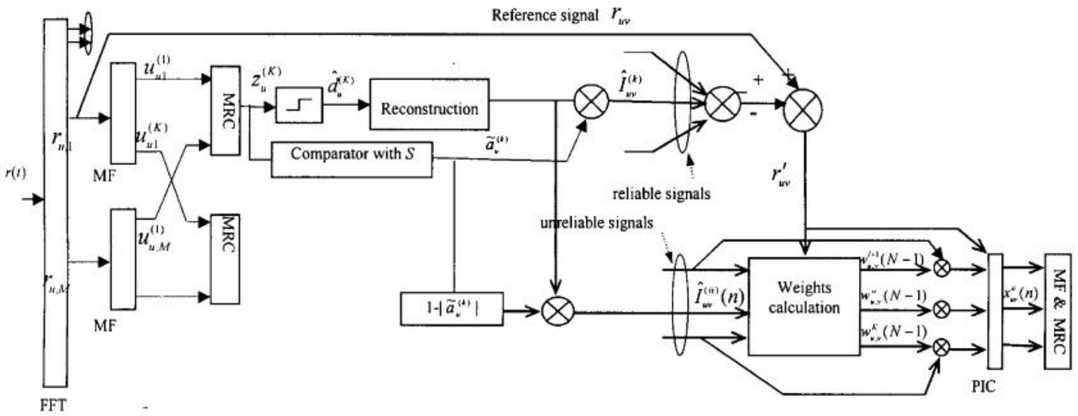

Figure 2. Selective adaptive receiver block diagram

With perfect channel estimation and a MRC diversity combining scheme, hence the desired signal D_{uv} is given by equation (5).

$$D_{uv} = \sqrt{\frac{2P}{M}} \frac{\alpha_{uv}^2}{2} \int_0^{T_s} b_u(t) dt = \sqrt{\frac{P}{2M}} g_{uv}^2 b_u T_s \tag{5}$$

The noise term N_{uv} has a zero mean Gaussian random variable and its variance is given by $\sigma_n^2 = \frac{N_o}{4} \sum_{v=1}^{M} \left[g_{uv}^2 \right]$. For Synchronous MC-DS-CDMA system, the multiuser interference from other subcarriers is simply vanishes due to orthogonality between subcarriers, while the source of multiuser interference comes from other users on the same considered subcarrier $I_1^{(k)}$, which can be written as equation (6).

$$\begin{aligned} I_1^{(k)} &= \sqrt{\frac{2P_k}{M}} \frac{\alpha_{uv}^k g_{uv}}{2} \cos(\theta_{uv}^k) \int_0^{T_s} b_u^k(t) c_k(t) c(t) dt \\ &= \sqrt{\frac{P_k}{2M}} \alpha_{uv}^k g_{uv} \cos(\theta_{uv}^k) b_u^k \rho_{ii,k}, \end{aligned} \tag{6}$$

Where $^{\circ}{}_{ii,k}$ is the correlation coefficient between the signature waveforms of the user of interest (k=ii) and the user k for the uth subcarrier.

3. Low complexity Selective Adaptive Parallel Interference Cancellation

The selective APIC is based on dividing users signals into reliable and unreliable signals. The M outputs of matched filter bank $u^{k}_{p,m}$ corresponding to the identical-bit streams are combined together using MRC, the soft output of MRC Z^{k}_{u} is compared to a suitable threshold value S to decide whether it's tentatively decision $\hat{b}^{k}_{u} = \mathrm{sgn}(Z^{k}_{u})$ is reliable or not, the output of the threshold comparator $\tilde{a}^{k}_{u}$ can be written as equation (7).

$$\tilde{a}^{k}_{u} = \begin{cases} 1 & Z^{k}_{u} \geq S, \\ 0 & -S \leq Z^{k}_{u} \leq S, \\ -1 & Z^{k}_{u} \leq S, \end{cases} \tag{7}$$

If $\left|\tilde{a}^{k}_{u}\right|$ =1, $\hat{b}^{k}_{u}$ is decided to be reliable otherwise, $\hat{b}^{k}_{u}$ is decided to be unreliable. The reliable signals are directly detected, while the unreliable signals are further processed with APIC scheme to get more re-estimate for them. In order to further illustrate this procedure let us assume that without loss of generality users $k=1,2,3,\ldots..,l$ are reliable, i.e.,$\left|Z^{k}_{u,v}\right| \geq S$ for, $1 \leq k \leq l$ while the other users $k = l+1,\ldots\ldots,K$ are unreliable, also the user ii is considered unreliable. The reconstructed signal of the kth user, uvth subcarrier, and n[th] chip is given by equation (8).

$$\hat{I}^{(k)}_{uv}(n) = \sqrt{\frac{P}{2M}}\, g^{(k)}_{uv} \cos(\ddot{\ }^{(k)}_{uv}) \hat{b}^{(k)}_{u} c_k(n) \tag{8}$$

The sum of all reconstructed reliable signals $k=1,2,3,\ldots..,l$ is subtracted from $r_{uv}(n)$ to get $r'_{uv}(n)$ which will be used as a reference signal to determine suboptimum weight for each unreliable signal. After subtracting the reconstructed reliable signals, APIC scheme will be applied as follows; the reconstructed signals of unreliable users are multiplied by their corresponding adaptive weights $w^{(k)}_{uv}(n)$ and summed together to produce an estimate $\hat{r}'_{uv}(n)$ of the reference signal $r'_{uv}(n)$, which can be expressed as equation (9).

$$\hat{r}'_{uv}(n) = \sum_{k=l+1}^{K} \hat{I}^{(k)}_{uv}(n) w^{(k)}_{uv}(n). \qquad 0 \leq n \leq N-1 \tag{9}$$

The difference between $r'_{uv}(n)$ and $\hat{r}'_{uv}(n)$ constitute the MAI estimation error for unreliable signals, based on this error, a cost function of the adaptive algorithm can be defined as equation (10).

$$£_{uv} = E\left[\left|e_{uv}(n)\right|^{2}\right] = E\left[\left|r'_{uv}(n) - \hat{r}'_{uv}(n)\right|^{2}\right], \tag{10}$$

Where E [.] is the statistical expectation operator and $e_{uv}(n) = r'_{uv}(n) - \hat{r}'_{uv}(n)$ is the error of the MAI estimation. In order to minimize the cost function, the weights $w_{uv}^{(k)}(n)$ are updated at the chip rate according to the Normalized LMS (NLMS) algorithm as equation (11)

$$w_{uv}^{(k)}(n+1) = w_{uv}^{(k)}(n) + \frac{« . \hat{I}_{uv}^{(k)}}{\sum_{k=l+1}^{K} [\hat{I}_{uv}^{(k)}]^2} [e_{uv}(n)]^*, \quad k \in [l+1:K], \tag{11}$$

Where « denotes the step-size, and initial value of weight $w_{uv}^{(k)}(0)$ of value 0 or 1.

At the end of one transmission interval (bit) the determined weight $w_{uv}^{(k)}(N-1)$ is used with the next stage (PIC) to obtain final decision for the unreliable signals. At PIC stage, sub-optimal weights $w_{uv}^{(k)}(N-1)$, are used to weight the input signal $\hat{I}_{uv}^{(k)}(n)$ over the entire transmission interval (bit). Subtracting the weighted MAI, the "cleaner" signal for the user ii is given by equation (12)

$$x_{uv}^{(ii)}(n) = r'_{uv}(n) - \sum_{\substack{k=l+1 \\ k \neq ii}}^{K} \hat{v}_{uv}^{(k)}(n), \tag{12}$$

Where $\hat{v}_{uv}^{(k)}(n)$ is given by equation (13).

$$\hat{v}_{uv}^{(k)}(n) = \hat{I}_{uv}^{(k)}(n) w_{uv}^{(k)}(N-1), \quad \text{for } k \in [l+1:K]. \tag{13}$$

The signal $x_{uv}^{(ii)}$ is then passed to the matched filter bank and the M outputs of matched filter bank are combined via MRC. The final decision for the unreliable signals is obtained according to equation (14).

$$\tilde{b}_u^{(ii)} = \mathrm{sgn}\{\Re[\sum_{n=0}^{N-1} \sum_{m=1}^{M} x_{uv}^{(ii)}(n) c^{(ii)}(n) g_{uv}^{(ii)}]\}. \tag{14}$$

After performing SA-PIC for unreliable signals, the final decision for all users are obtained as $\hat{b}_u = \sum_{k=1}^{l} \hat{b}_u^{(k)} + \sum_{k=l+1}^{K} \tilde{b}_u^{(k)}$, Where the first term represents the estimated data from the first stage (MF), while the second term represents the re-estimated data after APIC.

4. Computer Simulations and Results

In this section the performance of the low complexity receiver is evaluated by computer simulations. The MC-DS-CDMA system described in Section 2 is used in simulation. A random binary sequences of processing gain N=31 are used for data spreading. The diversity order M is set = 2. The threshold value S is normalized to the mean amplitude value of the decision variable Z_u. The total transmitted power is the same irrespective of the number of subcarriers, and a perfect power control system is assumed. The implementation complexity of the proposed scheme is discussed at the end of this Section.

Figure 3 and Figure 4 show the dependence of BER on the value of S for different values of Eb/No and for number of users 16, and 26 respectively. The figures show that at S=0.4, low BER can be obtained. It is also seen that increasing the value of S above 0.4 does not add significant performance gain but increases the complexity of the system. This result coincides with the conditional probability of error of the system given by (14).

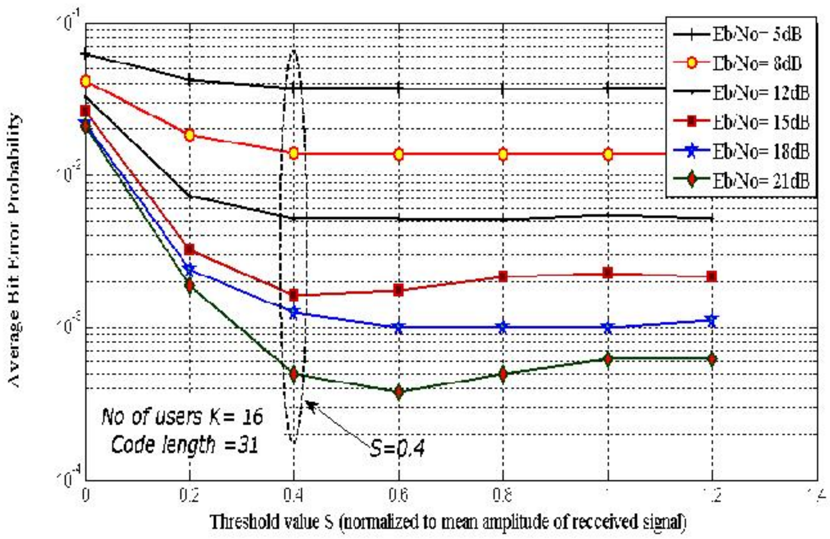

Figure 3. Dependence of average bit error probability of SA-PIC on the threshold value S (relative to mean amplitude value) for different Eb/No values, K= 1

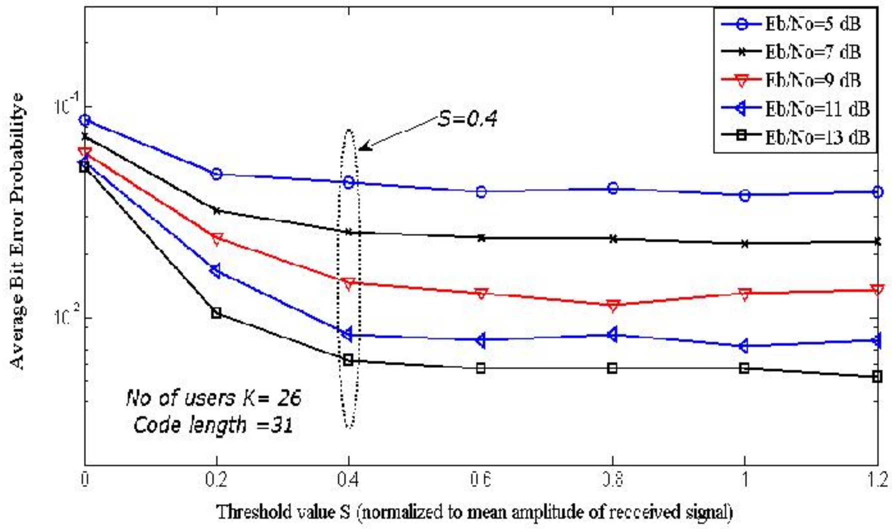

Figure 4. Dependence of average bit error probability of SA-PIC on the threshold value S for different Eb/No values, number of users K= 26

Figure 5 illustrates the performance of the SA-PIC for S= 0.4. The figure shows that the performance of SA-PIC is the same as the performance of APIC for different number of users K= 10, 16, 26. The benefit of using SA-PIC is that it has lower complexity than APIC as will indicated at the end of this section.

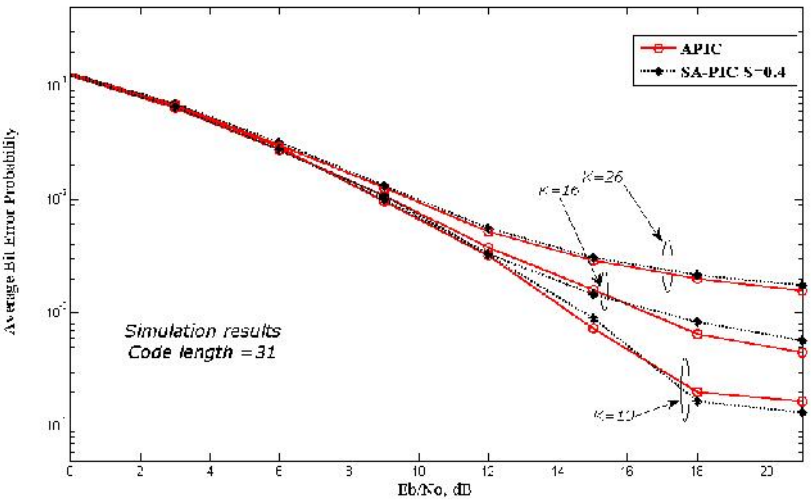

Figure.5. Bit error probability of APIC, SA-PIC for S=0.4, K=10, 16, and 26

Figure 6 depicts the performance comparison of SA-PIC, MF, CPIC, and APIC schemes. It is clear that SA-PIC scheme outperforms both MF and CPIC schemes, while its performance almost the same as APIC scheme. However, the SA-PIC algorithm allows the implementation complexity to be notably reduced with respect to APIC scheme as discussed at the end of this section.

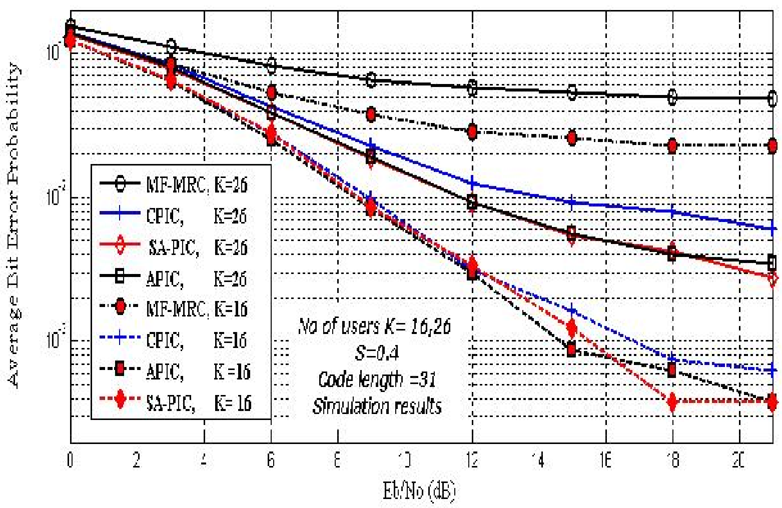

Figure 6. Comparisons of bit error probability for SA-PIC, CPIC, and APIC schemes for S=0.4, and K=16, 26 users

The SA-PIC scheme implementation complexity in terms of complex-valued operations is evaluated and compared with APIC under the same parameters. Table 1 shows the number of complex multiplication and addition per bit required to perform SA-PIC, and APIC schemes. The notations in the table are as follows. K denotes the number of users, M diversity order, N spreading gain, and L number of reliable signals. In Table 2, a numerical values of the number of multiplications and additions required by both schemes at. Different E_b / N_0 are calculated using the following parameters K=10, M=2, N=31, S=0.4, and the average value of L is estimated by simulation. Note that the complexity of the APIC scheme does not depend on E_b / N_0, while in SA-PIC scheme, the complexity depends on E_b / N_0 because the value of L depends on E_b / N_0. Table 2 shows that for practical values of E_b / N_0 the complexity of SA-PIC system is less than that one of the APIC scheme.

Table 1. Number of Complex Operations Required per Bit

Operation	SA-PIC		APIC	
	multiplication	addition	multiplication	addition
Comparator and subtract reliable signals	*MK*	*L*	-	-
Weights calculations	*NM[3(K-L)+2]*	*NM[3(K-L-1]*	*NM[3K+2]*	*NM[3K-1]*
Interference cancellation	*NM(K-L)[K-L-1]*	*NM(K-L)*	*NMK(K-1)*	*NMK*
Total	*NM[(K-L)(K-L+2)+2]+MK*	*NM[4(K-L)-3]+L*	*NM[K(K-1)+3K+2]*	*4NMK-NM*

Table 2. Numerical Values of Complex Operations Required per Bit

$\frac{E_b}{N_o}$ dB	SA-PIC (S=0.4)		APIC	
	multiplication	addition	multiplication	addition
0	1002	540	7564	2418
6	841	441		
12	757	392		
18	716	367		

5. Conclusion

A reduced complexity SA-PIC receiver with synchronous MC DS-CDMA system over Rayleigh fading channel has been investigated. The complexity of the receiver has been studied and compared with the APIC receiver. The performance of the receiver is evaluated by computer simulation and compared with the performance of different receivers. It has been shown that the performance of the low complexity SA-PIC receiver is same as APIC. The implementation complexity of this receiver in terms of number of multiplications and additions to be performed is lower than of the APIC receiver.

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