LETTER

GSIC Receiver with Adaptive MMSE Detection for Dual-Rate DS-CDMA System

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SUMMARY In this letter, we present groupwise successive interference cancellation (GSIC) receiver with adaptive minimum mean squared error (MMSE) detection and extended GSIC (EGSIC) receiver with adaptive MMSE detection for dual-rate DS-CDMA system. The receivers are GSIC receiver and EGSIC receiver combined with adaptive MMSE detection which is introduced to make initial bit detection more reliable. Furthermore, a multi-user detection scheme is introduced to mitigate the effect of multiple access interference (MAI) between users in a group which is usually ignored in conventional GSIC receiver and EGSIC receiver. Specifically, parallel interference cancellation (PIC) is adopted as a multi-user detection scheme within a group. It is shown that performance of the GSIC receiver and EGSIC receiver is significantly improved by employing adaptive MMSE detection. It is also shown that the performance of the receivers can be improved further by using PIC within a group.

key words: DS-CDMA, dual-rate, GSIC, MMSE, multi-user detection

1. Introduction

DS-CDMA has emerged as a promising multiple access technique for future wireless communication systems. Past efforts to achieve robust and efficient receivers for DS-CDMA systems had been focused mainly on constant bit-rate traffic such as voice. With the growth of wireless communication systems, there has been a considerable interest in providing several kinds of other communication services such as data, image, and video services that demand multi-rate transmission. To accommodate users with various data rates in a DS-CDMA system, the multiple processing gain (MPG) scheme is used [1]. In the MPG scheme, a user with high data rate has smaller processing gain and a user with low data rate has larger processing gain while their chip rates are the same. The signal of a high-rate user has larger amplitude than that of a low-rate user so that the former has same bit energy as the latter while the former has shorter bit duration than the latter.

Performance of a DS-CDMA system is limited by multiple access interference (MAI) and near-far effect. The difference of transmitted power between users makes the situation worse in the multi-rate DS-CDMA system with the MPG scheme. In order to mitigate the effect of MAI and achieve better performance, multi-user detectors have been proposed [2]. As a multi-user detector for multi-rate DS-CDMA system, groupwise successive interference cancellation (GSIC) receiver was proposed [3], [4]. In the GSIC receiver for the multi-rate DS-CDMA system, user signals are divided into groups according to data rates and signals for each group are estimated and subtracted successively from the received signal in an order of decreasing data rate. Extended GSIC (EGSIC) receiver was also considered as a multi-user detector for multi-rate DS-CDMA system [3]. While only the interference from higher-rate users to lower-rate users is considered in the GSIC receiver, an extra stage is added, which takes the interference from lower-rate users to higher-rate users into account, in the EGSIC receiver. The GSIC receiver and EGSIC receiver achieve performance improvement over the conventional matched filter (MF) receiver with moderate complexity and delay.

In the previous works, MF is used to obtain initial bit estimates that are used to cancel the MAI between groups. But the initial bit detection of MF suffers from MAI which comes from the user groups with lower data rates. The MAI between users in the same group is also a big threat to reliable bit detection. Hence, the performance of the GSIC receiver and EGSIC receiver can be improved by employing an advanced initial bit detection scheme and a method to mitigate the effect of MAI within a group.

In this letter, GSIC receiver with adaptive minimum mean squared error (MMSE) detection and EGSIC receiver with adaptive MMSE detection is proposed for dual-rate DS-CDMA system to overcome the shortcomings of the conventional GSIC receiver and EGSIC receiver. Adaptive MMSE detection is introduced to make more reliable initial bit detection than the MF [5]–[7]. Furthermore, parallel interference cancellation (PIC) is applied as a method to mitigate the effect of MAI between users within a group [8].

The rest of the paper is organized as follows. The system model is presented in Sect. 2. GSIC receiver with adaptive MMSE detection and EGSIC receiver with adaptive MMSE detection for dual-rate DS-CDMA system are described in Sect. 3. In Sect. 4, BER of the proposed receivers is shown by simulation and
compared with other receivers. Section 5 concludes the paper.

2. System Model

Consider a multi-rate DS-CDMA system with two data rates, i.e., a dual-rate DS-CDMA system. Extension to general multi-rate system is straightforward. Suppose that the MPG scheme is adopted to accommodate multi-rate users which are divided into 2 groups for their data rates. Let the number of users, the transmission rate of users, and the bit duration of the users in the group $n$ be denoted by $K_n$, $R_n$, and $T_n$, $n=1,2$, respectively. $R_1$ is an integer multiple of $R_2$, i.e., $R_1 = NR_2$ where $N > 1$. During the bit duration of a group 2 user $T_2$, a group 1 user transmits $N$ bits with bit duration $T_1 = T_2/N$. The processing gain of a group $n$ user is $L_n = T_n/T_c$, $n=1,2$, where chip duration $T_c$ is the same for users in all groups.

The baseband signal transmitted by the user $k$ in the group $n$ is given by

$$s_{k,n}(t) = \sqrt{E_b} \sum_m b_{k,n}[m] a_{k,n}(t - mT_n)$$

where $E_b$ is the bit energy, $b_{k,n}[m] \in \{-1,1\}$ is the $m$-th source bit of the user $k$ in the group $n$, and $a_{k,n}(t)$ is the normalized signature waveform of the user $k$ in the group $n$. $a_{k,n}(t)$ is given by

$$a_{k,n}(t) = \frac{1}{\sqrt{T_n}} \sum_{l=0}^{L_n-1} a_{k,n}[l] p_{T_c}(t - lT_c)$$

where $a_{k,n}[l] \in \{-1,1\}$ is the $l$-th chip of the signature waveform of the user $k$ in the group $n$. $p_{T_c}(t)$ is a unit amplitude rectangular pulse with duration $T_c$. In alternative form, $a_{k,n}(t)$ can be represented as a signature code vector $a_{k,n} = 1/\sqrt{T_n} \cdot (a_{k,n}[0], a_{k,n}[1], \cdots, a_{k,n}[L_n-1])^T$ where $(\cdot)^T$ denotes transpose. The signal transmitted by the user $k$ in the group $n$ propagates over a channel having fading of $\alpha_{k,n}$. The received baseband signal from the user $k$ in the group $n$ is given by

$$x_{k,n}(t) = \alpha_{k,n}s_{k,n}(t - \tau_{k,n})$$

$$= A_{k,n} \sum_m b_{k,n}[m] a_{k,n}(t - mT_n - \tau_{k,n})$$

where $\tau_{k,n}$ is the delay of the user $k$ in the group $n$ and $A_{k,n} = \alpha_{k,n}E_b$. The baseband signal received at the receiver is given by

$$r(t) = \sum_{n=1}^{N} \sum_{k=1}^{K_n} x_{k,n}(t) + n(t)$$

where $n(t)$ is an additive white Gaussian noise (AWGN) with the power spectral density of $N_0/2$ (W/Hz).

$r(t)$ is passed through a filter matched to the chip pulse shape and the output of the matched filter (MF) is sampled at the chip rate. For the user $k$ in the group $n$, the sample for the $l$-th chip of the $m$-th bit is given by

$$r_{k,n}[m,l] = \int_{mT_n+(l+1)T_c}^{mT_n+lT_c} r(t)\,dt.$$  

During each bit interval of the user $k$ in the group $n$, the $L_n$ chips are accumulated and stored in a vector as

$$r_{k,n}[m] = (r_{k,n}[m,0], r_{k,n}[m,1], \cdots, r_{k,n}[m,L_n-1])^T.$$  

Conventional MF receiver correlates the received vector for each bit with a local replica of the desired user’s signature code vector. The $m$-th bit estimates for the user $k$ in the group $n$ is given by

$$\hat{b}_{k,n}[m] = \text{sgn} \{a_{k,n}^T r_{k,n}[m]\}.$$  

3. GSIC Receiver with Adaptive MMSE Detection and EGUSIC Receiver with Adaptive MMSE Detection for Dual-Rate DS-CDMA System

Figure 1 shows the block diagram of the GSIC receiver with adaptive MMSE detection for dual-rate DS-CDMA system with the MPG scheme. It is assumed that the system is bit-synchronous.

Users are divided into 2 groups for their data rates: high-rate (HR) users (group 1) and low-rate (LR) users (group 2). Initial bit estimates for the group 1 users are obtained by adaptive MMSE detection [5]–[7]. The adaptive MMSE detection is a near-far resistant single-user detection which does not need any side information other than the desired user’s signature waveform and timing. The adaptive MMSE detection has computational complexity that is only slightly greater than that of the conventional MF detection [6]. For the user $k$ in the group 1, the decision statistic from adaptive MMSE detection for the $m$-th bit, $\tilde{b}^{(M)}_{k,1} [m]$, is given by

$$\tilde{b}^{(M)}_{k,1} [m] = c_{k,1}[m]^T r_{k,1}[m]$$

where $c_{k,1}[m] = 1/\sqrt{T_1} \cdot (c_{k,1}[m,0], c_{k,1}[m,1], \cdots,$

![Fig. 1 Block diagram of the GSIC receiver with adaptive MMSE detection for the dual-rate DS-CDMA system with the MPG scheme.](image-url)
$c_{k,1}[m, L_1 - 1]^T$ denotes the code vector for adaptive MMSE detection of the m-th bit and the superscript $(M)$ represents the adaptive MMSE detection stage. The $m$-th bit estimate for the user $k$ in the group 1 is given by

$$\hat{b}_{k,1}^{(M)}[m] = \text{sgn}(\tilde{b}_{k,1}^{(M)}[m]).$$  \hfill (8)

In general, the code vector for adaptive MMSE detection for the user $k$ in the group $n$, $c_{k,n}[m]$, is derived from the MMSE criterion, which is obtained by minimizing $E[|\hat{y}_{k,n}^{(M)}[m] - \tilde{b}_{k,n}^{(M)}[m]|^2]$. It is convenient to decompose $c_{k,n}[m]$ into two components as $c_{k,n}[m] = a_{k,n} + w_{k,n}[m]$ where $a_{k,n}$ is the fixed component which is the signature code vector and $w_{k,n}[m]$ is the adaptive component for the $m$-th bit of the user $k$ in the group $n$. To obtain the adaptive component with affordable computational complexity, normalized least mean squared error (LMS) algorithm is applied [7]. The equation for updating $w_{k,n}[m]$ is given by

$$w_{k,n}[m] = w_{k,n}[m - 1] + 2\mu \frac{1}{||r_{k,n}[m]||^2} \times \left( \tilde{b}_{k,n}^{(M)}[m - 1] - \tilde{b}_{k,n}^{(M)}[m \mid m - 1] \right) r_{k,n}[m]$$  \hfill (9)

where $\mu$ is the step size. The initial value for $w_{k,n}[m]$ is all zero vector of length $L_n$.

Now, we have initial bit estimates for the group 1 users which are obtained from adaptive MMSE detection. Then, the effect of MAI between users in the group 1 is mitigated by an interference cancellation scheme. Here, we adopt parallel interference cancellation (PIC) within a group. PIC is suitable to be used within a group since the received signal power is approximately equal for all users in a group in an average sense [3]. Using the initial bit estimates for the group 1 users, the estimates for the received signals are regenerated for those users. After adaptive MMSE detection, the estimate for the received signal of the user $k$ in the group 1 is given by

$$\tilde{x}_{k,1}^{(M)}(t) = \hat{A}_{k,1} \sum_m \tilde{b}_{k,1}^{(M)}[m] a_{k,1}(t - mT_1)$$  \hfill (10)

where $\hat{A}_{k,1}$ is the estimate for $A_{k,1}$. The estimates for the received signal of all users in the group 1 but one for the user $k$ in the group 1 are summed up to obtain the MAI estimate for the user $k$ in the group 1. For each user in the group 1, the MAI estimate is subtracted from the received signal and its result is passed on to the MF bank. For the user $k$ in the group 1, the received signal after subtracting MAI is given by

$$r_{k,1}^{(I)}(t) = r(t) - \sum_{l=1,l \neq k}^{K_1} \tilde{x}_{l,1}^{(M)}(t)$$  \hfill (11)

where the superscript $(I)$ represents interference cancellation stage. For the user $k$ in the group 1, the updated bit estimate for the $m$-th bit, $\hat{b}_{k,1}^{(I)}[m]$, is given by

$$\hat{b}_{k,1}^{(I)}[m] = \text{sgn} \left( a_{k,1}^T r_{k,1}^{(I)}[m] \right)$$  \hfill (12)

where $r_{k,1}^{(I)}[m]$ is the vector of chip rate samples of $r_{k,1}^{(I)}(t)$ for the $m$-th bit and is defined in similar manner as (9). Then, the estimates for the received signals of the group 1 users are regenerated using the updated bit estimates. After the interference cancellation, the estimate for the received signal of the user $k$ in the group 1 is given by

$$\tilde{x}_{k,1}^{(I)}(t) = \hat{A}_{k,1} \sum_m \hat{b}_{k,1}^{(I)}[m] a_{k,1}(t - mT_1).$$  \hfill (13)

The estimates for the received signals of the group 1 users are summed up and subtracted from the received signal. The received signal after subtracting MAI from the group 1 users is given by

$$r'(t) = r(t) - \sum_{l=1}^{K_1} \tilde{x}_{l,1}^{(I)}(t).$$  \hfill (14)

The initial bit estimates for the group 2 users are obtained by adaptive MMSE detection using $r'(t)$. Using the initial bit estimates for the group 2 users, the MAI between the group 2 users is cancelled by PIC and updated bit estimates for the group 2 users are obtained. This completes the process in the GSIC receiver with adaptive MMSE detection.

Above GSIC receiver with adaptive MMSE detection considers only the interference from the HR users to the LR users. But when there are many LR users, the MAI from the LR users to the HR users is not negligible. Figure 2 shows the block diagram of the EG Sic receiver with adaptive MMSE detection for dual-rate DS-CDMA system with the MPG scheme. In the EG Sic receiver with adaptive MMSE detection, the MAI from the LR users are regenerated and cancelled from the

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**Fig. 2** Block diagram of the extended GSIC receiver with adaptive MMSE detection for the dual-rate DS-CDMA system with the MPG scheme.
received signal. Then, the bit detection process for the HR users, which is composed of adaptive MMSE detection and following PIC, is repeated using the received signal with MAI from the LR users being subtracted.

Note that, for the LR users, the performance of the GSIC receiver is the same as that of the EGSIC receiver as shown in Fig. 1 and Fig. 2. However, we expect that the EGSIC receiver achieves better performance than the GSIC receiver for the HR users.

4. Simulation Results

Consider a synchronous dual-rate DS-CDMA system with the MPG scheme. Suppose that BPSK is used as a modulation scheme and the ratio \( N \) between the data rate of the HR users and that of the LR users is 8. A random signature sequence of length 16 is assigned to each HR user and one of length 128 is assigned to each LR user. Assume that the channel for each user has independent identically distributed frequency-flat Rayleigh fading. Also assume that the receiver knows the signature sequences of all users and has perfect synchronization and channel estimation for each user. Later in this section, we will discuss about the effect of imperfect channel estimation on the performance of the receivers considered. The value of step size \( \mu \) for the adaptive MMSE detection is set as 1/16. The number of stages for PIC is 1. The number of the LR users and that of the HR users are 8 and 4, respectively.

Figure 3 shows the BER of the MF receiver, GSIC receiver, GSIC receiver with adaptive MMSE detection (GSIC/MMSE), GSIC receiver with PIC (GSIC/PIC), and GSIC receiver with both adaptive MMSE detection and PIC (GSIC/MMSE&PIC) for the HR users. In the following, if ‘PIC’ is not contained explicitly in the name of a certain receiver, PIC is not performed within a group. Note that the performance of the MF receiver is the same as that of the GSIC receiver for the HR users. Since the MAI from the LR users is not cancelled from the received signal, the amount of performance improvement for all multi-user detectors is limited.

Figure 4 shows the BER of the MF receiver, EGSIC receiver, EGSIC receiver with adaptive MMSE detection (EGSIC/MMSE), EGSIC receiver with PIC (EGSIC/PIC), and EGSIC receiver with both adaptive MMSE detection and PIC (EGSIC/MMSE&PIC). Figure 4(a) and Fig. 4(b) show the BER of various receivers for the LR users and for the HR users, respectively. It is shown in Fig. 4(a) that the EGSIC receiver achieves some performance improvement over the MF receiver. It is shown that the BER can be lowered by employing adaptive MMSE detection for initial bit detection or PIC within a group. It is also shown that the EGSIC/MMSE&PIC receiver achieves significant performance improvement over the conventional EGSIC receiver for the LR users. It is shown in Fig. 4(b) that the BER of the EGSIC receiver can be lowered by using adaptive MMSE detection or PIC. It is also

![Fig. 3 BER of GSIC receiver with adaptive MMSE detection for the HR users for dual-rate DS-CDMA system with the MPG scheme in a Rayleigh fading channel for 8 LR and 4 HR users and \( N = 8 \).](image)

![Fig. 4 BER of EGSIC receiver with adaptive MMSE detection for dual-rate DS-CDMA system with the MPG scheme in a Rayleigh fading channel for 8 LR and 4 HR users and \( N = 8 \).](image)
shown that the EGSIC/MMSE&PIC receiver have significantly lower BER than the conventional EGSIC receiver for the HR users. Note that the trends in BER curves are different for the LR users in Fig. 4(a) and for the HR users in Fig. 4(b). It is shown in Fig. 4 that we can achieve more performance improvement for the LR users than for the HR users when the EGSIC receiver is used instead of the MF receiver. This can be explained as follows. For the LR users in Fig. 4(a), MAI from the HR users is cancelled from the received signal. Since the HR users’ signals have much larger power than those of the LR users, the performance of the LR users is much improved by the cancellation of MAI from the HR users. In contrast, the signal power of the LR user is much smaller than that of the HR users. Hence, the subtraction of MAI from the LR users does not result in as much improvement for the HR users as the case for the LR users. When we compare the EGSIC receiver and EGSIC/MMSE receiver, the situation is different. Since the number of HR users is the half of that of LR users, the application of adaptive MMSE detection is more effective for the HR users. When PIC is applied in the EGSIC receiver, the MAI within a group is explicitly cancelled by PIC. Hence, the performance improvement of the EGSIC/PIC receiver over the EGSIC receiver is larger for the LR user group which is with more users than the HR user group. Finally, the EGSIC/MMSE&PIC receiver achieves the lowest BER for both the LR users and the HR users.

It is of great importance to see the influence of imperfect channel estimation on the performance of the proposed receivers. We assume the channel estimation error, $A_{k,n} - \hat{A}_{k,n}$, has Gaussian distribution with zero mean. The exact distribution of the channel estimation error may not have Gaussian distribution. But, it is simple to model and it is sufficient for our purpose to simply see the effect of channel estimation error on the performance of the receivers considered. As a measure for the accuracy of the channel estimation, we use normalized standard deviation $\sigma$ which is defined as

$$
\sigma = \left( \frac{E[|\hat{A}_{k,n} - A_{k,n}|^2]}{E[|A_{k,n}|^2]} \right)^{1/2}
$$

where $E[\cdot]$ denotes expectation. $\sigma = 0.00$ corresponds to the case of perfect channel estimation. As $\sigma$ gets larger, the quality of channel estimation gets poorer. Table 1 and Table 2 show the influence of channel estimation error on the performance of various receivers for the LR users and for the HR users at $E_b/N_0 = 25$ dB. It is shown that the MF receiver is not affected from channel estimation error. The performance of the EGSIC receiver is relatively robust to channel estimation error. It can tolerate channel estimation error up to $\sigma = 0.10$ with less than 10% increase in BER. EGSIC/MMSE receiver is also robust to channel estimation error. EGSIC/PIC receiver is more sensitive than previous two receivers. EGSIC/MMSE&PIC receiver, which achieves the lowest BER among the receivers, is most sensitive to channel estimation error. To maintain satisfactory performance for the EGSIC/MMSE&PIC receiver, it is required to keep $\sigma$ less than 0.05. It can be concluded from Table 1 and Table 2 that a receiver with better performance is more sensitive to channel estimation error. But, if it is possible to limit channel estimation error within a reasonable bound, the EGSIC/MMSE&PIC receiver still provides much improved performance.

### Table 1 Influence of channel estimation error on the performance of various receivers

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<th>Normalized std. dev. $\sigma$</th>
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<th>0.04</th>
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<th>0.08</th>
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### Table 2 Influence of channel estimation error on the performance of various receivers

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### 5. Conclusion

In this letter, GSIC receiver with adaptive MMSE detection and EGSIC receiver with adaptive MMSE detection are proposed for dual-rate DS-CDMA system with the MPG scheme. The adaptive MMSE detection employed in the proposed receivers is implemented by simple normalized LMS algorithm so that it improves the performance of the receivers with little added computational complexity over the MF. Furthermore, PIC
is adopted as a multi-user detection scheme within a group. It is shown from the simulation results that the performance of the GSIC receiver and EGSIC receiver can be improved significantly by employing both advanced initial bit detection scheme and interference cancellation scheme within a group, simultaneously. Even when there is channel estimation error, the proposed receivers still provide improved performance provided that the channel estimation error is kept within a reasonable bound.

References