LETTER

# Adaptive Multi-Stage Parallel Interference Cancellation Receiver for Multi-Rate DS-CDMA System*

**Seung Hee HAN**[†a)], ***Student Member and*** **Jae Hong LEE**[†], ***Nonmember***

**SUMMARY** In this letter, adaptive multi-stage parallel interference cancellation (PIC) receiver is considered for multi-rate DS-CDMA system. In each stage of the adaptive multi-stage PIC receiver, multiple access interference (MAI) estimates are obtained by the sub-bit estimates from the previous stage and the adaptive weights for the sub-bit estimates. The adaptive weights are obtained by minimizing the mean squared error between the received signal and its estimate through normalized least mean square (LMS) algorithm. It is shown that the adaptive multi-stage PIC receiver achieves smaller BER than the matched filter receiver, multi-stage PIC receiver, and multi-stage partial PIC receiver for the multi-rate DS-CDMA system in a Rayleigh fading channel.

***key words:*** *DS-CDMA, multi-rate, multi-user detection, PIC*

## 1. Introduction

Wireless communication systems are to support various communication services, such as voice, data, image, and video services that demand multi-rate transmission [1]. Users are to transmit their information with various data rates and their performance requirements will vary from application to application. To accommodate users with various data rates in a direct-sequence code division multiple-access (DS-CDMA) system, multiple processing gain (MPG) scheme is used [2]. 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 fixed 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.

The performance of a multi-rate DS-CDMA system is severely degraded by multiple access interference (MAI), difference of transmitted power between users, and near-far effect. Multi-user detectors are adopted to mitigate the performance degradation due to MAI and near-far effect. Huge potential capacity and performance improvement is expected as a result of using multi-user detector at the expense of increased complexity [3]–[5]. A multi-stage parallel interference cancellation (PIC) receiver achieves performance improvement with moderate complexity and delay as a multi-user detector [6].

In the multi-stage PIC receiver, however, the performance is not always improved as the number of stages increases, especially when the number of users approaches the processing gain of the DS-CDMA system. To improve the performance of the multi-stage PIC receiver, it was proposed to cancel MAI partially by introducing a partial cancellation factor in each stage [7]. For a DS-CDMA system, an adaptive multi-stage PIC receiver was proposed in which MAI estimates are obtained using bit estimates from the previous stage and adaptive weights for the bit estimates [8]. The adaptive weights are obtained by minimizing the mean squared error between a received signal and its estimate. It is shown that the adaptive multi-stage PIC receiver has lower bit error rate (BER) than the matched filter (MF) receiver and multi-stage partial PIC receiver for the DS-CDMA system.

In this letter, the adaptive multi-stage PIC receiver is considered for the multi-rate DS-CDMA system with the MPG scheme and its bit error rate (BER) is obtained for a Rayleigh fading channel by simulation.

## 2. System Model

Consider an asynchronous multi-rate DS-CDMA system. Suppose that the MPG scheme is adopted to accommodate multi-rate users that are divided into $N$ groups for their data rates. Let the number of users and the bit duration of the users in the group $n$ be denoted by $K_n$ and $T_n$, $n = 1, 2, \cdots, N$, respectively. Let the transmission rate of users in the group $n$, $R_n$, be an integer multiple of $R_1$, i.e. $R_n = M_n R_1$, $n = 1, 2, \cdots, N$, with restriction that $1 = M_1 < M_2 < \cdots < M_N$ and $M_n$ divides $M_N$, $n = 1, 2, \cdots, N$. During the bit duration of a group 1 user $T_1$, a group $n$ user transmits $M_n$ bits with bit duration $T_n = T_1/M_n$. Assume that the chip duration $T_c$ is same for users in all groups. Then the processing gain of a group $n$ user becomes $L_n = T_n/T_c = L_1/M_n$, $n = 1, 2, \cdots, N$. The baseband signal transmitted by the user $k$ in the group $n$ is given by

$$s_{k,n}(t) = \sqrt{E_b} \sum_{m} b_{k,n}[m] a_{k,n}(t - mT_n) \qquad (1)$$

where $E_b$ is the bit energy, $b_{k,n}[m] \in \{-1, 1\}$ is the $m$-th source bit, 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

Manuscript received January 30, 2004.
Manuscript revised March 16, 2004.

[†]The authors are with the School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea.
a) E-mail: shhan75@snu.ac.kr

*This work was supported in part by the Brain Korea 21 project and the ITRC program of the Korean Ministry of Information and Communications.

$$a_{k,n}(t) = \frac{1}{\sqrt{T_n}} \sum_{l=0}^{L_n-1} a_{k,n}[l] p_{T_c}(t - lT_c) \quad (2)$$

where $a_{k,n}[l]$ is the $l$-th chip of the signature waveform of the user $k$ in the group $n$, $l = 0, 1, \cdots, L_n - 1$, and $p_{T_c}(t)$ is a rectangular pulse with unit amplitude and duration $T_c$. Assume that transmitted signal of 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

$$\begin{aligned} x_{k,n}(t) &= \alpha_{k,n} s_{k,n}(t - \tau_{k,n}) \\ &= A_{k,n} \sum_m b_{k,n}[m] a_{k,n}(t - mT_n - \tau_{k,n}) \end{aligned} \quad (3)$$

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

$$\begin{aligned} r(t) &= \sum_{n=1}^{N} \sum_{k=1}^{K_n} x_{k,n}(t) + n(t) \\ &= \sum_{n=1}^{N} \sum_{k=1}^{K_n} \sum_m A_{k,n} b_{k,n}[m] a_{k,n}(t - mT_n - \tau_{k,n}) \\ &\quad + n(t) \end{aligned} \quad (4)$$

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

At the matched filter (MF) output for the user $k$ in the group $n$, the decision statistic for the $m$-th bit is given by

$$\tilde{b}_{k,n}[m] = \int_{mT_n+\tau_{k,n}}^{(m+1)T_n+\tau_{k,n}} r(t) a_{k,n}(t - mT_n - \tau_{k,n}) dt. \quad (5)$$

For the user $k$ in the group $n$, the $m$-th bit estimate is given by

$$\hat{b}_{k,n}[m] = \mathrm{sgn}(\tilde{b}_{k,n}[m]) \quad (6)$$

where $\mathrm{sgn}(\cdot)$ is the signum function defined as

$$\mathrm{sgn}(u) \equiv \begin{cases} 1, & u \geq 0, \\ -1, & u < 0. \end{cases} \quad (7)$$

## 3. Adaptive Multi-Stage PIC Receiver for Multi-Rate DS-CDMA System

In the adaptive multi-stage PIC receiver for the multi-rate DS-CDMA system with the MPG scheme, a bit of a group $n$ user is divided into $T_n/T_N$ sub-bits whose bit duration equals the bit duration of the highest-rate user $T_N$. For a highest-rate user, a bit corresponds to a sub-bit. Figure 1 shows the block diagram of the $s$-th stage of the adaptive multi-stage PIC receiver for the multi-rate DS-CDMA system with the MPG scheme. Initial sub-bit estimates for the adaptive multi-stage PIC receiver are obtained by the MF bank which is referred to as the stage 0. For the user $k$ in the group $n$ in the stage 0, the decision statistic for the $i$-th sub-bit $d_{k,n}^{(0)}[i]$ is given by

$$\begin{aligned} \tilde{d}_{k,n}^{(0)}[i] = &\int_{iT_N+\tau_{k,n}}^{(i+1)T_N+\tau_{k,n}} r(t) \\ &\times a_{k,n}\left(t - \left\lfloor i \frac{M_n}{M_N} \right\rfloor T_n - \tau_{k,n}\right) dt \end{aligned} \quad (8)$$

where $\lfloor x \rfloor$ is the greatest integer that does not exceed $x$. In the stage 0, the $i$-th sub-bit estimate for the user $k$ in the group $n$ is given by

$$\hat{d}_{k,n}^{(0)}[i] = \mathrm{sgn}(\tilde{d}_{k,n}^{(0)}[i]). \quad (9)$$

Assume that the sub-bit estimates for all users are obtained for the $(s-1)$th stage. In the $s$-th stage, $s = 1, 2, \ldots, S-1$, the estimate for $x_{k,n}(t)$ of the user $k$ in the group $n$, $\hat{x}_{k,n}^{(s)}(t)$, is obtained using the sub-bit estimates of the previous stage $\hat{d}_{k,n}^{(s-1)}[i]$, adaptive weights for the sub-bit estimates $\lambda_{k,n}^{(s-1)}[i]$, the signature waveform $a_{k,n}(t)$, and the estimate for signal amplitude $\hat{A}_{k,n}$ for the user $k$ in the group $n$. The estimates for $x_{k,n}(t)$ in the $s$-th stage is given by

$$\begin{aligned} \hat{x}_{k,n}^{(s)}(t) = \hat{A}_{k,n} &\sum_i \lambda_{k,n}^{(s-1)} \hat{d}_{k,n}^{(s-1)}[i] \\ &\times a_{k,n}\left(t - \left\lfloor i \frac{M_n}{M_N} \right\rfloor T_n - \tau_{k,n}\right) \\ &\times p_{T_N}(t - iT_N - \tau_{k,n}) \end{aligned} \quad (10)$$

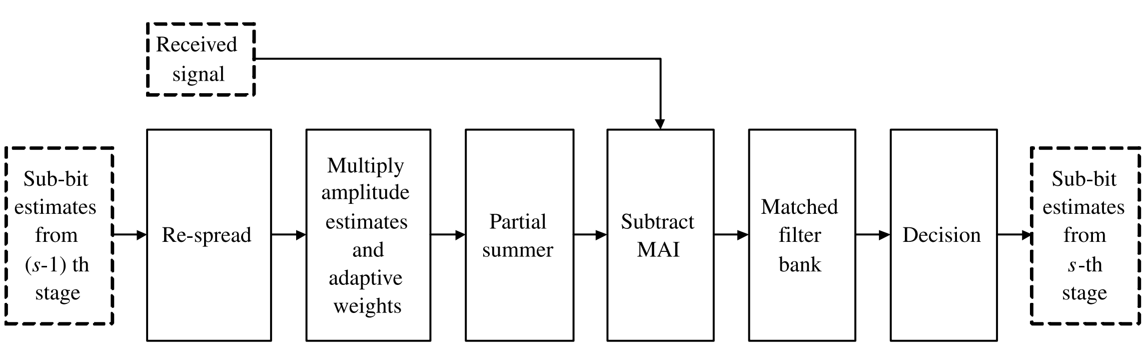



**Fig. 1** Block diagram of the $s$-th stage of the adaptive multi-stage PIC receiver for the multi-rate DS-CDMA system.

where $p_{T_N}(t)$ is the rectangular pulse with unit amplitude and duration $T_N$.

The adaptive weights are set taking the reliability of each sub-bit estimate into consideration. With $\lambda_{k,n}^{(s-1)}[i] = 1$, the adaptive multi-stage PIC receiver is the same as the conventional multi-stage PIC receiver for the multi-rate DS-CDMA system [9]–[11]. To obtain the adaptive weights, the received signal is sampled at the chip-rate. Suppose that the delay of each user is an integer multiple of chip duration, i.e. $\tau_{k,n} = \xi_{k,n} T_c$, for some integer $\xi_{k,n}$, $k = 1, 2, \cdots, K_n$, $n = 1, 2, \cdots, N$. The received signal after chip-rate sampling is given by (11) at the bottom of the page where $n[j]$ is the noise sample. In the $s$-th stage, the estimate for the received signal after chip-rate sampling is given by (12) at the bottom of the page. The adaptive weights are obtained by minimizing the mean squared error between the received signal and its estimate, i.e. the adaptive weights must minimize $E(|r[j] - \hat{r}^{(s)}[j]|^2)$. The adaptive weights are adjusted by a normalized least mean square (LMS) algorithm and updated every chip duration. Let the initial value of the adaptive weight for the $i$-th sub-bit of the user $k$ in the group $n$, $\lambda_{k,n}^{(s-1)}[i]$, be denoted by $\lambda_{k,n}^{(s-1)}[i][0] = 1$ and the adaptive weight after the $l$-th iteration be denoted by $\lambda_{k,n}^{(s-1)}[i][l]$. For the $i$-th sub-bit of the user $k$ in the group $n$ in the $s$-th stage, $s = 1, 2, \cdots, S-1$, the adaptive weight after the $l$-th iteration is given by (13) at the bottom of the page where $u = iL_N + l - 1 - \xi_{k,n}$ is a temporary index, $e^{(s)}[j] = r[j] - r^{(s)}[j]$ is the error between the received signal and its estimate, and $\mu^{(s)}$ is the step size of the normalized LMS algorithm for the $s$-th stage. The adaptive weight after $L_N - 1$ iterations, $\lambda_{k,n}^{(s-1)}[i][L_N - 1]$, is used as the adaptive weight value for the $i$-th sub-bit of the user $k$ in the group $n$ in the $s$-th stage.

Users with different data rates have different level of adaptive weights since the signature waveforms have different magnitudes according to data rates. From (2), we can see that the chip value of the signature waveform of the users in the group $n$ has magnitude inversely proportional to $\sqrt{T_n}$. In general, the longer the symbol duration or equivalently the lower the data rates, the smaller the adaptive weight value. For the LMS algorithm to converge, $\mu^{(s)}$ has to satisfy the condition of $0 < \mu^{(s)} < 2$. Although larger step size achieves faster convergence in the LMS algorithm, it causes larger gradient noise when the adaptive weights are misadjusted.

The partial summer sums up the estimates for the received signals of all users but the user $k$ in the group $n$ to obtain MAI estimate for the user $k$ in the group $n$. For each user the MAI estimate is subtracted from the received signal and its result is passed on to the MF bank of the $s$-th stage. After MAI is subtracted in the $s$-th stage, the received signal of the user $k$ in the group $n$ is given by

$$r_{k,n}^{(s)}(t) = r(t) - \sum_{(l,h)\neq(k,n)} \hat{x}_{l,h}^{(s)}(t). \tag{14}$$

In the $s$-th stage, the $i$-th sub-bit estimate for the user $k$ in the group $n$ is given by

$$\begin{aligned} \hat{d}_{k,n}^{(s)}[i] &= \mathrm{sgn}(\tilde{d}_{k,n}^{(s)}[i]) \\ &= \mathrm{sgn}\left(\int_{iT_N+\tau_{k,n}}^{(i+1)T_N+\tau_{k,n}} r_{k,n}^{(s)}(t) \right. \\ &\qquad \left. \times\, a_{k,n}\left(t - \left\lfloor i\frac{M_n}{M_N}\right\rfloor T_n - \tau_{k,n}\right) dt\right) \end{aligned} \tag{15}$$

where $\tilde{d}_{k,n}^{(s)}[i]$ is the decision statistic for the $i$-th sub-bit. The sub-bit estimates are updated in each stage using the sub-bit estimates from the previous stage. In the $S$-th stage of the multi-stage PIC receiver, the $m$-th bit estimate for the user $k$ in the group $n$ is obtained as

$$\hat{b}_{k,n}[m] = \mathrm{sgn}\left\{\sum_{i=m(M_N/M_n)}^{(m+1)(M_N/M_n)-1} \lambda_{k,n}^{(S)}[i]\tilde{d}_{k,n}^{(S)}[i]\right\}. \tag{16}$$

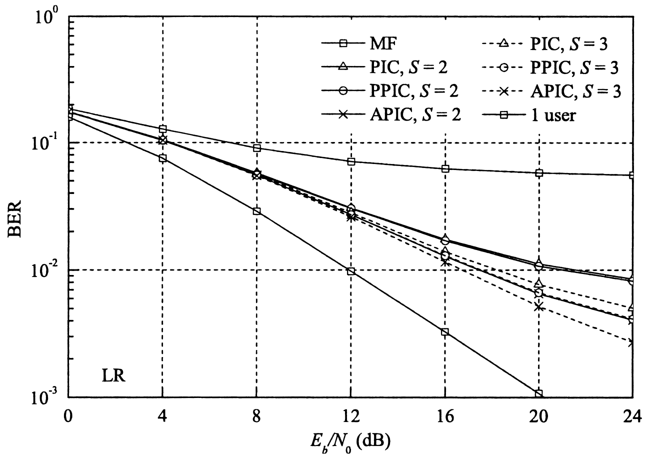
## 4. Simulation Results and Discussions

Consider an asynchronous multi-rate DS-CDMA system with the MPG scheme for three data rates: high-rate (HR), medium rate (MR), and low-rate (LR). Suppose that BPSK is used as a modulation scheme and the Gold code of length 31 is repeated once, 4, and 16 times during bit duration of HR, MR, and LR users as a signature sequence for each user, respectively. Assume that the channel for each user has independent identically distributed frequency-flat Rayleigh fading with normalized Doppler frequency $f_m T_1 = 0.01$ where $T_1$ is the bit duration of the low-rate user. Assume that the system is chip-synchronous and each interfering user's propagation delay is an integer multiple of chip duration. Also assume that the receiver knows the signature sequences of all users and has perfect power control for slow fading and path-loss. In each stage, the amplitude of the received signal of each user is estimated from the decision statistic in

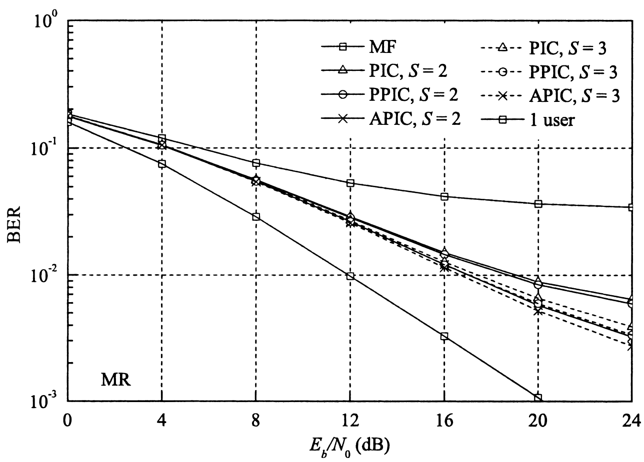
$$r[j] = \sum_{n=1}^{N}\sum_{k=1}^{K} A_{k,n} b_{k,n}\left[\lfloor (j-\xi_{k,n})/L_n \rfloor\right] a_{k,n}\left[(j-\xi_{k,n}) \bmod L_n\right] + n[j] \tag{11}$$

$$\hat{r}^{(s)}[j] = \sum_{n=1}^{N}\sum_{k=1}^{K} \hat{A}_{k,n}\lambda_{k,n}^{(s-1)}\left[\lfloor (j-\xi_{k,n})/L_n \rfloor\right] \hat{d}_{k,n}^{(s-1)}\left[\lfloor (j-\xi_{k,n})/L_n \rfloor\right] a_{k,n}\left[(j-\xi_{k,n}) \bmod L_n\right] \tag{12}$$

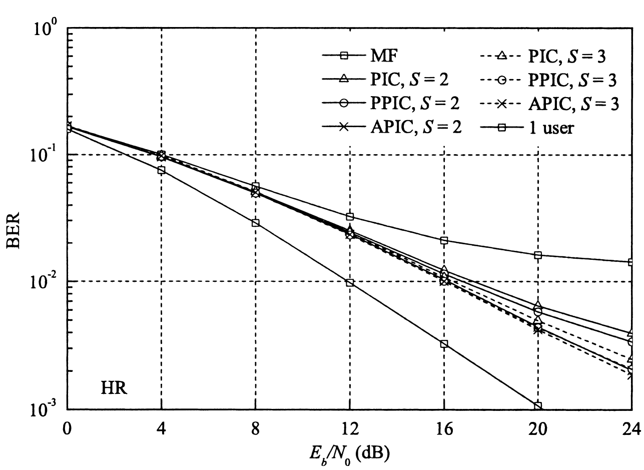
$$\lambda_{k,n}^{(s-1)}[i][l] = \lambda_{k,n}^{(s-1)}[i][l-1] + \frac{\mu^{(s)}}{\left|\sum_{n=1}^{N} K_n\right|^2} \hat{d}_{k,n}^{(s-1)}[i] a_{k,n}\left[u \bmod L_n\right] e^{(s)}\left[u\right], l = 1, 2, \cdots, L_N - 1 \tag{13}$$




(a) LR user




(b) MR user




(c) HR user

**Fig. 2** BER of the adaptive 2- and 3-stage PIC receivers for the multi-rate DS-CDMA system with the MPG scheme in a Rayleigh fading channel (8 LR, 4 MR, 2 HR users).

the previous stage.

Figure 2 shows the BER of adaptive 2- and 3-stage PIC (APIC) receiver with $\mu^{(1)} = 1.0$, $\mu^{(2)} = 0.5$, $\mu^{(3)} = 0.2$ in a Rayleigh fading channel for 8 LR, 4 MR, and 2 HR users. It is compared with the BER of the conventional 2- and 3-stage PIC receiver, the 2- and 3-stage partial PIC (PPIC) receiver, and the MF receiver. Figure 2(a) shows the BER of LR users. In Fig. 2(a) it is shown that various multi-stage PIC receivers achieve much smaller BER than the MF receiver. It is shown that adaptive 2-stage PIC receiver achieves smaller BER than the 2-stage PIC receiver and the 2-stage partial PIC receiver. It is also shown that the adaptive 3-stage PIC receiver has smaller BER than 3-stage receivers of other types for LR users. Figure 2(b) shows the BER of MR users. In Fig. 2(b) it is shown that adaptive 2-stage PIC receiver achieves smaller BER than the 2-stage PIC receiver and the 2-stage partial PIC receiver for MR users. It is shown that the adaptive 3-stage PIC receiver has smaller BER than 3-stage receivers of other types for MR users. Figure 2(c) shows the BER of HR users. In Fig. 2(c) it is shown that the adaptive 3-stage PIC receiver has smaller BER than other 3-stage receivers for HR users. In Fig. 2(a), Fig. 2(b), and Fig. 2(c), it is also shown that the adaptive 2-stage PIC receiver achieves BER performance close to the 3-stage partial PIC receiver for all groups. It is also shown in Fig. 2(a), Fig. 2(b), and Fig. 2(c) that the performance trends are similar but specific values are different for users with different data rates. It is basically due to that users with different data rates experience different levels of interference. The transmitted signal power is generally larger for users with higher data rates, so users with lower data rates experience relatively higher level of interference than users with higher data rates. So, the performance of MF receiver is better for users with higher data rates. On the other hand, the adaptive multi-stage PIC receiver achieves performance improvement over the MF receiver, multi-stage PIC receiver, multi-stage partial PIC receiver for all user groups with different data rates. After applying the adaptive 3-stage PIC receiver, all user groups achieve similar BER performance.

## 5. Conclusions

In this letter, the adaptive multi-stage PIC receiver is extended to the multi-rate DS-CDMA system with the MPG scheme. A bit of each user is divided into sub-bits and multi-user detection is applied for sub-bits. In each stage of the adaptive multi-stage PIC receiver, MAI estimates are obtained using the sub-bit estimates from the previous stage and the adaptive weights for the sub-bit estimates. The adaptive weights for the sub-bit estimates are obtained by a normalized LMS algorithm. In the final stage, the decision statistics for the sub-bits originated from one bit are combined to form final bit estimate. It is shown that the adaptive multi-stage PIC receiver has significant performance improvement over the conventional MF receiver for the multi-rate DS-CDMA system. It is also shown that the adaptive multi-stage PIC receiver achieves smaller BER than the multi-stage PIC receiver and the multi-stage partial PIC receiver for users with various data rates in a Rayleigh fading channel.

## References

[1] T. Ojanperä and R. Prasad, "An overview of air interface multiple access for IMT-2000/UMTS," IEEE Commun. Mag., vol.36, no.9, pp.82–95, Sept. 1998.

[2] T. Ottosson and A. Svensson, "On schemes for multirate support in DS-CDMA systems," Wirel. Pers. Commun., vol.6, no.3, pp.265–287, March 1998.

[3] M. Saquib, R. Yates, and N. Mandayam, "Decorrelating detectors for a dual rate synchronous DS/CDMA system," Proc. IEEE VTC'96, pp.377–381, Atlanta, GA, U.S.A., April–May 1996.

[4] H. Ge and J. Ma, "Multi-rate LMMSE detectors for asynchronous multi-rate CDMA systems," Proc. IEEE ICC'98, pp.714–718, Atlanta, GA, U.S.A., June 1998.

[5] C.S. Witjing, T. Ojanpera, M.J. Juntti, K. Kansanen, and R. Prasad, "Groupwise serial multiuser detectors for multirate DS-CDMA," Proc. IEEE VTC'99, pp.836–840, Houston, TX, U.S.A., May 1999.

[6] M.K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," IEEE Trans. Commun., vol.38, no.4, pp.509–519, April 1990.

[7] D. Divsalar and M.K. Simon, "Improved CDMA performance using parallel interference cancellation," Proc. IEEE MILCOM'94, pp.911–917, Fort Monmouth, NJ, U.S.A., Oct. 1994.

[8] G. Xue, J. Weng, T. Le-Ngoc, and S. Tahar, "Adaptive multistage parallel interference cancellation for CDMA," IEEE J. Sel. Areas Commun., vol.17, no.10, pp.1815–1827, Oct. 1999.

[9] S.H. Han and J.H. Lee, "Multi-stage partial parallel interference cancellation receivers for multi-rate DS-CDMA system," IEICE Trans. Commun., vol.E86-B, no.1, pp.170–180, Jan. 2003.

[10] S.H. Han and J.H. Lee, "Multi-stage partial parallel interference cancellation receivers for multi-rate DS-CDMA," Proc. MoMuC 2000, pp.P-25-1–P-25-5, Tokyo, Japan, Oct. 2000.

[11] S.H. Han and J.H. Lee, "Performance of multi-rate DS-CDMA system with multi-stage partial parallel interference cancellation," Proc. IEEE VTC 2000-Spring, pp.765–769, Tokyo, Japan, May 2000.

[12] S.H. Han and J.H. Lee, "Adaptive multi-stage parallel interference cancellation receiver for multi-rate DS-CDMA system," Proc. IEEE VTC 2001-Fall, pp.591–594, Atlantic City, NJ, U.S.A., Oct. 2001.