다중경로 환경하에서의 다이버시티 수신을 이용한 다중사용자 수신기

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Multiuser Receiver with Diversity Detection for DS/CDMA Systems under Multipath Fading

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요 약

CDMA 시스템에서 다중 사용자 간섭과 원근효과에 대한 문제점을 해결하기 위하여 많은 다중 사용자 수신기가 제안되었다. 간섭 사용자의 수신 신호를 이용하여 다중 사용자 간섭을 제거하는 다중 사용자 수신기는 CDMA 시스템의 용량 증가를 가져온다.

본 논문에서는 다중 경로 페이딩 채널에 대처하기 위해 다중 경로 다이버시티, 다중 사용자 검출과 신호의 결정 귀환을 이용한 다중 경로 역상관 결정귀환 수신기를 제안하였다. 또한, 제안된 수신기의 성능 비교를 위하여 주파수 선택적 레일리 페이딩 채널하에서 오류 확률을 유도하였다. 해석적 분석 결과에 의해 본 논문에서 제안된 수신기가 기존의 수신기에 비해서 시스템의 성능을 크게 향상시킴을 보였다.

ABSTRACT

Several multiuser detectors have been recently proposed to combat multiple-access interference and near-far problem for CDMA systems. Multiuser detectors, exploiting knowledge of other users to cancel multiple-access interference, have the potential to provide a significant increase in capacity of CDMA systems. In this paper, we propose a suboptimal multiuser receiver that combines multipath diversity reception, multiuser detection and decision-feedback cancellation. Also, the performance analysis of the proposed multiuser receiver is developed for frequency selective Rayleigh fading channels. Numerical results show that the proposed receiver provides a significantly enhanced performance.

I. Introduction

In a DS/CDMA(Direct Sequence/Code Division Multiple Access) communication environment, there are a number of users to transmit their signals over a common channel. Since the conventional single user detector ignores the presence of interfering signals, it performs poorly as the number of users increases. Thus, the conventional approach causes two problems: multiple-access interference (MAI) and near-far problem. So far, several multiuser detectors have been proposed to combat these problems. The optimum multiuser detector has, however, a complexity that grows exponentially with the number of users[1]. On the other hand, the decorrelating detector, which consists of a bank of matched filters and a decorrelating matrix, has not only a significant performance gain over the conventional one but also linear complexity. However, a disadvantage of this detector is an

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increase in the noise power due to the inversion of the channel performed by the decorrelating filter. Duel-Hallen introduced decorrelating decision-feedback(DF) detector that utilizes decisions of the stronger users. It's shown that the decorrelating DF scheme approaches the optimum performance as the power of interfering signal increases.

In wireless communications environments, multi-path fading places fundamental limitations on the performance of the systems. Thus, diversity techniques are often used to combat the effect of multipath fading. In [2], Zvonar and Brady proposed a linear multipath decorrelating receiver which eliminates the effects of MAI prior to the diversity combining process. However, this receiver suffers from the performance loss due to the noise enhancement in decorrelating operations similar to the decorrelating detector over AWGN channel.

In this paper, we propose a suboptimal multiuser receiver that combines multipath diversity reception, multiuser detection and decision-feedback cancellation based on the idea of decorrelating DF detector in [3]. Also, analytical expressions for the error probability of the proposed multiuser receiver are derived for frequency selective Rayleigh fading channels. Numerical results show that the proposed receiver provides a significantly enhanced performance.

Ⅱ. System Description

In this communication systems, we consider a synchronous coherent BPSK CDMA system with K users simultaneously transmitting their signals over frequency selective Rayleigh fading channels. The modeling of each channel link follows that of Zvonar and Brady[2]. In CDMA systems, since a bandwidth of the transmitted signal is much greater than the coherence bandwidth of the channel, $W \gg (\Delta f)_c$, the channel can be said to be frequency-selective. Also, we suppose that the symbol interval T is smaller than the coherence time of the channel, that is $T \ll (\Delta t)_c$ [5]. This fading condition allows us to estimate the channel characteristics perfectly. The impulse response of the multipath channel for the k^{th} user is of the form

$$h_k(t) = \sum_{l=0}^{L-1} c_{k,l}(t)\,\delta(t - lT_c) \tag{1}$$

where the coefficients $c_{k,l}$ are independent complex Gaussian random variables due to the Rayleigh fading of the k^{th} user and T_c is the chip period. The equivalent lowpass signature waveform of the k^{th} user is given by $\sqrt{w_k}\, s_k(t)\, e^{j\phi_k}$ where $s_k(t)$ is the normalized signature waveform, and w_k, ϕ_k are signal power and carrier phase of the k^{th} user, respectively. The received signal from k^{th} user is given by

$$m_k(t) = s_k^T \sqrt{w_k}\, \phi_k \overline{c_k} b_k \tag{2}$$

where $\overline{c_k} = [c_{k,0} \cdots c_{k,L-1}]^T$ is the channel coefficients vector for user k, $\phi_k = e^{j\phi_k} I_L$ and $s_k^T = [s_k(t)\; s_k(t-T_c) \;\; \cdots s_k(t-(L-1)T_c)]$. Then, the total received baseband signal is

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} \sum_{l=0}^{L-1} \sqrt{w_k}\, c_{k,l}(t)\, s_k(t - lT_c)\, b_k e^{j\phi_k} + n(t) \\ &= \sum_{k=1}^{K} m_k(t)\, b_k + n(t) = S^T W \Phi C b + n(t) \end{aligned} \tag{3}$$

where

$$S = [\, \overline{s_1}^T \; \overline{s_2}^T \cdots \overline{s_k}^T]^T \tag{4}$$

$$C = diag(\overline{c_1}\; \overline{c_2} \cdots \overline{c_K}) \tag{5}$$

$$W = diag(W_1\; W_2 \; \cdot\cdot\cdot \; W_K) \tag{6}$$

$$\Phi = diag(\phi_1\; \phi_2 \; \cdot\cdot\cdot \; \phi_K), \tag{7}$$

and $W_k = \sqrt{w_k}\, I_L$, $b = [b_1\; b_2 \;\; \cdot\cdot\cdot b_K]^T$.

Ⅲ. Multipath Decorrelating Decision-Feedback Multiuser Receiver

In [2], the linear multipath decorrelating receiver consists of a bank of KL filters matched to delayed versions of the users' signature waveforms followed by the decorrelating filter. The outputs of a given user are then whitened by the whitening filter and optimally combined.

Introducing the DF cancellation similar to that of the decorrelating DF detector over AWGN channel in [3] into the multipath decorrelating detection, we can derive the multipath decorrelating DF multiuser receiver(MDDFR) which combines multipath diversity reception, multiuser detection and decision-feedback cancellation, as shown in Fig. 1. The received signal $r(t)$ is pass through a bank of KL matched filters. The outputs sampled at the symbol interval T are given by

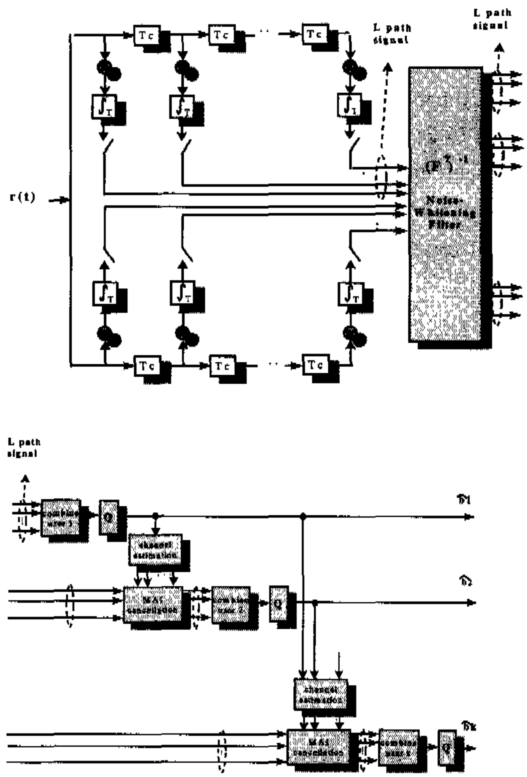

Fig. 1 Block diagram of multipath decorrelating decision-feedback receiver.

$$y = R W \Phi C b + n \tag{8}$$

where the cross-correlation matrix is

$$R = \int_0^T S S^T(t)\, dt, \tag{9}$$

and n is a Gaussian vector with covariance matrix $N_0R/2$. Instead of using decorrelating filter, we apply a noise whitening filter $(F^T)^{-1}$, which is obtained by Cholesky factorization of cross-correlation matrix $R=F^TF$ [3]. The resulting output vector is

$$\bar{y} = (F^T)^{-1} y = F W \Phi C' b + n_w \tag{10}$$

where n_w is a white Gaussian noise vector with zero mean. Following the whitening filter, maximal-ratio combining with filter $\overline{c_1}^H (F_{11})^T$, where F_{ij} is the i,j^{th} $L \times L$ block of F, is performed for the first decision device. This decision is then used for subtracting MAI from the signal of the second decision device, and so on. We assume that the averaging output values over previous n_b bits are used for estimating the signal amplitude for each user and that decisions are made in the order of decreasing strengths. Using the channel coefficients and the decisions of the stronger users, maximal-ratio combining with combing filter $\overline{c'_k}^H (F_{kk})^T$, where $\overline{c'_k}$ is channel coefficients vector of the k^{th} strongest user, is performed for the k^{th} decision device.

After processing DF operations, the decision variable for the k^{th} decision device can be written as

$$z_k = \overline{c'_k}^H F_{kk}^T F_{kk} \overline{c'_k} \sqrt{w_k}\, b_k + \overline{c'_k}^H (F_{kk})^T \sum_{i=1}^{k-1} F_{ki} \overline{c'_i} \left(\sqrt{w_i}(b_i - \hat{b}_i) + \Delta w_i b_i \right) \tag{11}$$

where $\Delta w_i \triangleq \sqrt{w_i} - \sqrt{\hat{w}}$ means a amplitude estimate error, and $\hat{b}_i$, $\hat{w}_i$ denote the estimates of b_i, w_i. We assume that $c'_{k,l}$, $l = 0, \dots, L-1$ are independent identically distributed (iid) random variables and transmitting power of each user is w. Then, the ordering of decreasing strengths is obtained by sorting the energy estimates of channel coefficients $x_1 \geq x_2 \geq \cdots \geq x_K$, where $x_k = \overline{c'_k}^H \overline{c'_k}$. The variance of Δw can be obtained from the fact that the variance of the noise in the estimate of the amplitude over n_b bits intervals decreases by a factor of $1/n_b$[8]. Using the Gaussian approximation for large k, we can obtain the variance of noise for k^{th} decision device conditioned on $\overline{c'_k}$; N_k as follows:

$$Var(N_k) = Var(N_{k,I}) + Var(N_{k,II}) + Var(N_{k,III}) \quad (12)$$

where

$$Var(N_{k,I}) = Var(\overline{c'_k}^H (F_{kk})^T n_w)$$
$$= \overline{c'_k}^H (F_{kk})^T F_{kk} \overline{c'_k} N_0/2 \quad (13)$$

$$Var(N_{k,II}) = Var(\overline{c'_k}^H (F_{kk})^T \sum_{i=1}^{k-1} F_{ki} \overline{c'_i} \Delta w b_i)$$
$$= \sum_{i=1}^{k-1} [\overline{c'_k}^H (F)_{kk}^T (F)_{ki} (F)_{ki}^T (F)_{kk} \overline{c'_k}$$
$$\times \frac{E[x_i]}{L} \frac{Var(N_i)}{n_b}] \quad (14)$$

$$Var(N_{k,III}) = Var(\overline{c'_k}^H (F_{kk})^T \sum_{i=1}^{k-1} F_{ki} \overline{c'_i} \sqrt{w} \Delta b_i)$$
$$= \sum_{i=1}^{k-1} [\overline{c'_k}^H (F)_{kk}^T (F)_{ki} (F)_{ki}^T (F)_{kk} \overline{c'_k}$$
$$\times \frac{E[x_i]}{L} 4 w P_e^i], \quad (15)$$

where P_e^i is error probability of the i^{th} decision device. Then, the error probability of the k^{th} decision device, conditioned on $\overline{c'_k}$, can be expressed as

$$P_e^k(z_k \mid \overline{c'_k}) = Q(\sqrt{\frac{|\overline{c'_k}^H F_{kk}^T F_{kk} \overline{c'_k}|^2 w}{Var(N_k)}}) \quad (16)$$

Now letting

$$\Psi_k = (F)_{kk}^T (F)_{kk} N_0/2 + \sum_{i=1}^{k-1} [(F_{kk})^T F_{ki} (F_{ki})^T F_{kk}$$
$$\times \frac{E[x_i]}{L} (\frac{Var(N_i)}{n_b} + 4 w P_e^i)], \quad (17)$$

we can obtain the upper and lower bounds to $P_e^k(z_k)$ as

$$E_{x_k}[P_k(z_k \mid x_k)] \ge F_P(\frac{\lambda_{k,\max}^n}{\lambda_{k,\min}^D}) \quad (18)$$

$$E_{x_k}[P_k(z_k \mid x_k)] \le F_P(\frac{\lambda_{k,\min}^n}{\lambda_{k,\max}^D}) \quad (19)$$

where $F_P(\chi) = E_{x_k}[Q(\sqrt{x_k w \chi})]$, $\lambda_{k,\max}^n = \max\{\lambda_{k,1}^n, \dots, \lambda_{k,L}^n\}$, $\lambda_{k,1}^n, \dots, \lambda_{k,L}^n$ and $\lambda_{k,1}^D, \dots, \lambda_{k,L}^D$ are the eigenvalues of $F_{kk}^T F_{kk}$ and Ψ_k, respectively, and $x_i = \overline{c'_i}^H \overline{c'_i}$. If difference between λ_{min} and λ_{max} is small, $F_P(\chi)$, $(\lambda_{k,\min}^n/\lambda_{k,\max}^D) < \chi < (\lambda_{k,\max}^n/\lambda_{k,\min}^D)$, will agree closely with $P_e^k(z_k)$. Then, using the mean value of eigenvalues, we can approximate the unconditional BER of the k^{th} decision device as

$$P_e^k(z_k) = \int_0^\infty P_e^k(z_k \mid x_k) f_{X_k}(x_k)\, dx_k \quad (20)$$

$$\approx \int_0^\infty Q(\sqrt{\frac{x_k w \lambda_{k,m}^n}{\lambda_{k,m}^D}}) f_{X_k}(x_k)\, dx_k \quad (21)$$

where $f_{X_k}(x_k)$ is the pdf(probability density function) of x_k, $\lambda_{k,m}^n = \text{mean}\{\lambda_{k,1}^n, \dots, \lambda_{k,L}^n\}$. The approximation in Eq. (21) is verified by comparing result of Eq. (21) with that of Eq. (20) in section IV.

Using the order statistics[6], the pdf(probability density function) $f_{X_k}(x_k)$ of the k^{th} strongest user's signal can be expressed as

$$f_{X_k}(x) = k\binom{K}{k} F_X^{K-k}(x) [1 - F_X(x)]^{k-1} f_X(x) \quad (22)$$

where

$$F_X(x) = 1 - \sum_{l=0}^{L-1} \frac{1}{l!} (\frac{x}{\bar{x}}) e^{-\frac{x}{\bar{x}}} \quad (23)$$

$$f_X(x) = \frac{1}{(L-1)!\, \bar{x}^L} x^{L-1} e^{-\frac{x}{\bar{x}}}, \quad (24)$$

and $\bar{x} = E[c'_{k,l} c'^*_{k,l}]$. Using the expansions in Eqs. (25) and (26)

$$(u+v)^n = \sum_{k=0}^{n} \binom{n}{k} u^{n-k} v^k \quad (25)$$

$$(\sum_{k=0}^{m} a_k x^k)^n = \sum_{k=0}^{mn} c_k x^k \quad (26)$$

where

$$c_i = \begin{cases} c_0 = a_0^n \\ c_i = \frac{1}{i a_0} \sum_{k=0}^{i} (kn - i + k) a_k c_{i-k}, & 1 \le i \le mn \end{cases}, \quad (27)$$

and we may express Eq. (22) as

$$f_{x_k}(x) = k\binom{K}{k}\sum_{m=0}^{K-k}\binom{K-k}{m}(-1)^m \times \sum_{l=0}^{(L-1)n} g_l(m,k)\left(\frac{x}{\bar{x}}\right)^l \times e^{-(m+k)\frac{x}{\bar{x}}} \frac{1}{(L-1)!\,\bar{x}}\left(\frac{x}{\bar{x}}\right)^{L-1} \quad (28)$$

where

$$g_l(m,k) = \begin{cases} 1, & l=0 \\ \frac{1}{a_0}\sum_{i=1}^{l}[in-l+i]a_i g_{l-i}, & 1\le l\le (L-1)n \end{cases}$$

$$a_i = \begin{cases} \frac{1}{i!}, & 0\le i\le L-1 \\ 0, & i\ge L-1 \end{cases}, \quad (29)$$

and $n=m+k-1$. Then, substituting Eq. (28) into Eq. (21), the error probability of the k^{th} decision device can be approximated as

$$P^k_{MDDF} \cong \frac{k}{2}\binom{K}{k}\sum_{m=0}^{K-k}\binom{K-k}{m}(-1)^m \quad (30)$$

$$\times\left(\sum_{l=0}^{(L-1)(m+k-1)} g_l(m,k)\frac{(l+L-1)!}{(L-1)!}\frac{1}{(m+k)^{l+L}}\right)$$

$$\times\left[1-u_{mk}\sum_{j=0}^{l+L-1}\binom{2j}{j}\left(\frac{1-u_{mk}}{2}\right)^j\left(\frac{1+u_{mk}}{2}\right)^j\right]$$

where

$$u_{mk} = \sqrt{\frac{\bar{x}}{\bar{x}+\alpha_{k,mean}(m+k)}} \quad (31)$$

$$\alpha_{k,mean} = \frac{2\lambda^D_{k,mean}}{w\lambda^n_{k,mean}}. \quad (32)$$

Finally, the average error probability is obtained by averaging the BER from all decision devices.

Ⅳ. Numerical Results

In this section, we give numerical results to compare the detectors in previous sections. The results were obtained with Gold sequences of length 127, and an estimate interval of signal amplitude n_b=10 bits. Each of the multipath is assumed to be separated by T_c interval.

In section III, we approximated the error probability by using the mean value of eigenvalues. In Fig. 2, we compare the results from Eqs. (20) and (21) for 20 users and 2-4 paths. The BER results from Eqs. (20) and (21) are obtained by averaging the conditional error rates over 1000 independent channels. As shown in Fig. 2, we note that the approximation with the mean value of eigenvalues in Eq. (21) shows good accuracy in this communication case.

In Fig. 2, we compare the performance of MDDFR, MDR, conventional RAKE receiver, and RAKE receiver in isolated transmission for 15 users and 2, 4 paths. In the nume ≤rical results, the BER performance results for k5 are obtained by averaging the conditional error probability over 1000 independent channels, and for k>5, Eq. (30) was used. As shown in Fig. 2, the proposed receiver supports more improved performance when signal to noise ratio gets higher. Figure 3 shows the average BER plots versus E_b/N_o for 20 users. It is shown that the performance of the proposed scheme is conspicuous compared to conventional one. In Fig. 4, the average BER curves are shown as a function of the number of users. As can be seen from Fig. 4, MDR is more sensitive to the number of users. Figures 2 through 4 show the proposed receiver has superior performance to the previous receivers. The performance gains of MDDFR over MDR are more significant for large value of L. To maintain BER obtained with the RAKE receiver using the same number of paths in isolated transmission, the power in receivers using the decorrelating operations should be increased. Therefore, this power loss due to decorrelation can be called decorrelation loss[7]. In Fig. 5, we compare the decorrelation losses of MDR and MDDFR for different orders of multipath diversity. From Fig. 5, we can see that the decorrelation loss of MDR increases compared to that of MDDFR, as the number of users and paths increase. Also, we note that the users in an MDR system must transmit with about 1-2dB more energy per bit to maintain the same performance of an MDDFR.

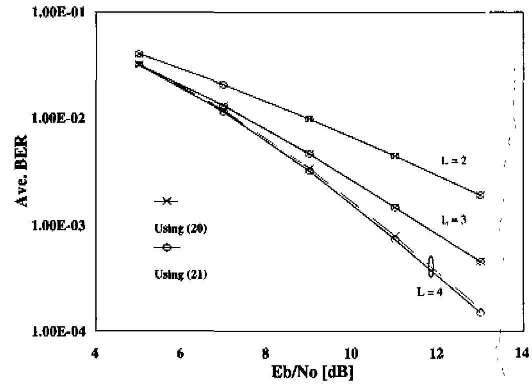

Fig. 2 Average BER vs. E_b/N_o under Multipath fading (K=20).

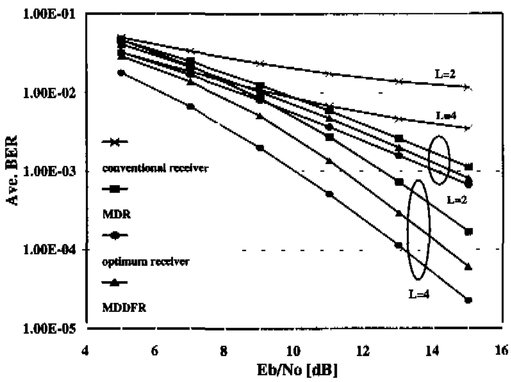

Fig. 3 Average BER vs. E_b/N_0 under multipath fading (K=15).

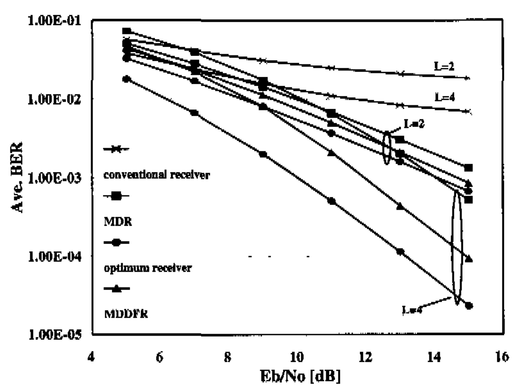

Fig. 4 Average BER vs. E_b/N_0 under multipath fading (K=20).

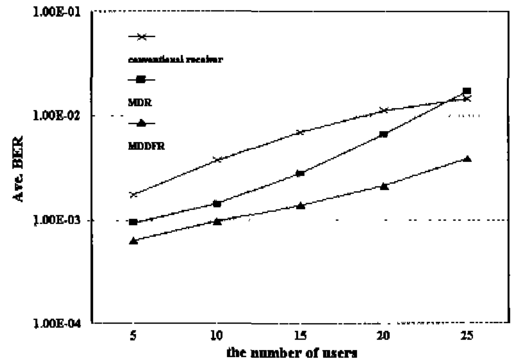

Fig. 5 Average BER vs. the number of users under multipath fading (L=4, E_b/N_0=11dB).

V. Conclusions

In this paper, we proposed a suboptimal multiuser receiver that combines multipath diversity reception,

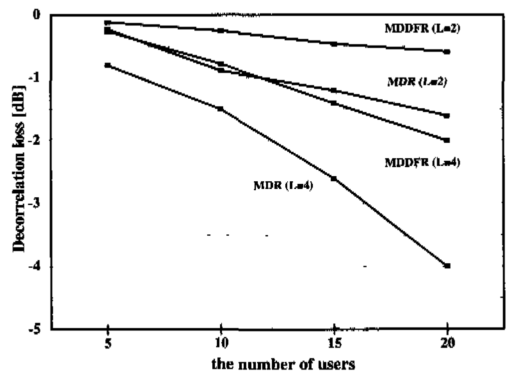

Fig. 6 Decorrelation loss vs. the number of users under multipath fading (P_e = 10E-3).

multiuser detection, and decision-feedback cancellation. Also, the performance analysis of the proposed receiver was developed for frequency selective Rayleigh fading channels. Numerical results indicate that the proposed receiver provides a significantly enhanced performance.

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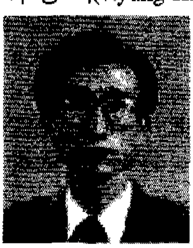

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