Joint AIC and ML Decoder Scheme for a Space-Time Coded DS-CDMA System*

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SUMMARY In this paper, a joint adaptive interference canceller (AIC) and maximum likelihood (ML) decoder scheme is proposed for a space-time coded DS-CDMA system with the difference between arrival times from transmit antennas. As the arrival time difference causes not only ISI and MAI, but also inter-antenna interference, performance degradation in the space-time coded DS-CDMA system is more severe than that of a regular DS-CDMA system with single transmit antenna. To mitigate the effect of the interference during space-time decoding, a joint algorithm for the proposed scheme merges adaptation process of the AIC into a ML decoding algorithm. Performance of the proposed scheme is evaluated for QPSK space-time trellis codes with two transmit antennas. It is shown that the proposed scheme achieves better performance than the conventional ML decoding scheme.

key words: DS-CDMA, space-time code, adaptive interference canceller, ML decoder

1. Introduction

As the space-time coding technique obtains both diversity gain and coding gain by using multiple transmit and receive antennas, it is applied to the code-division multiple-access (CDMA) system recently [1], [2]. In most previous works on the space-time codes, it is assumed that the channel between each pair of transmit and receive antennas has i.i.d. Rayleigh fading and all signals from the transmit antennas arrive at same time in the receiver. However, in reality, a signal from each transmit antennas have arrival time difference by large separation between the transmit antennas to make the channels independent to each other or by propagation through multipaths. Arrival time difference causes inter-symbol interference (ISI) and inter-antenna interference (IAI), which means the interference by the desired signals with the difference arrival delays from other antennas in the receiver matched to the arrival delay from one transmit antenna, to degrade the performance of the space-time coded system. To mitigate the degradation of performance, an interference cancellation scheme is applied to a downlink of the space-time coded DS-CDMA system. As an interference cancellation scheme the adaptive interference canceller (AIC) achieves better performance than a conventional matched-filter (MF) detector without increasing receiver complexity much and need for additional side-information in a mobile station. The AIC consisting of delay-taps and weight-taps cancels MAI and ISI by updating the tap-weights based on the previous bit-decisions [3]–[5]. As adaptation process of the AIC works by the symbol, it is difficult to apply the AIC to the space-time coded DS-CDMA system of which decoding process works by the frame. In this paper, a joint AIC and ML decoder scheme is proposed for a space-time coded DS-CDMA system to mitigate the effect of the interferences during space-time decoding. To merge adaptation process of the AIC into the ML decoding algorithm, a joint algorithm for the proposed scheme is presented in which the error signal of the LMS algorithm for the AIC is obtained by reading the Euclidean distance from the memory of the ML decoder at each symbol time. This paper is organized as follows. In Sect. 2 the space-time coded DS-CDMA system is described. In Sect. 3 the joint AIC and ML decoder scheme is proposed. Simulation results are presented in Sect. 4 and conclusions are drawn in Sect. 5.

2. System Model

Consider the downlink of a DS-CDMA system with processing gain N having K simultaneous users. Figure 1 shows the block diagram of the space-time coded DS-

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CDMA system with $L$ transmit and $M$ receive antennas. The $i$th data bit of the $k$th user, $b_k(i)$, is space-time encoded to a codeword $x_k(i) = (x_k^1(i), \ldots, x_k^K(i))$ for $L$ transmit antennas. Each symbol of the codeword $x_k(i)$ is spread by its unique signature sequence $a_k = [a_{k,0}, a_{k,1}, \ldots, a_{k,N-1}]$ to be transmitted with symbol energy $E_s$, $E_s = E_0/L$, where $E_0$ is bit energy. The signature waveform for the $k$th user is given by

$$a_k(t) = \sum_{n=0}^{N-1} a_{k,n} \varphi(t - nT_c) \quad (1)$$

where $T_c$ is chip duration, and $\varphi(t)$ is a rectangular chip-pulse with unit energy. Assume that the channel between each pair of transmit and receive antennas has independent and identically distributed (i.i.d.) Rayleigh fading to each other. Then the received baseband signal at the $m$th receive antenna is given by

$$r_m(t) = \sqrt{E_s} \sum_{l=0}^{L-1} \sum_{i=1}^F h_m^l(t) \cdot \sum_{n=1}^K x_k^l(i) a_k(t - iT_s - \tau_m^l) + n_m(t) \quad (2)$$

where $F$ is the length of a frame, $T_s$ is symbol duration, $h_m^l(t)$ is the channel gain, $\tau_m^l$ is arrival time delay from the $l$th transmit antenna to the $m$th receive antenna, and $n_m(t)$ is a Gaussian noise with the power spectral density of $N_0$.

Assume that the fading gain of each channel is constant over one frame and varies from frame to another. During each symbol duration, $N$ output samples from the $m$th chip matched-filter make a received signal vector $r_m(i) = [r_{m,0}(i), r_{m,1}(i), \ldots, r_{m,N-1}(i)]$ for the $m$th receive antenna. Denote $\mathbf{a}_k^d$ as the $d$-shifted sequence for the signature sequence of the $k$th user, $a_k$. The $n$th component of $\mathbf{a}_k^d$, $n = 1, 2, \ldots, N$, is given by

$$[\mathbf{a}_k^d]_n = \begin{cases} a_{k,n-dI_n} & \text{for } 0 \leq d < N - 1, \\ a_{k,n+dI_n-N} & \text{for } N + 1 \leq d < 0 \end{cases} \quad (3)$$

where $I_A = \{ 1, \text{ if A occurs} \} \{ 0, \text{ otherwise} \}$ is the indicator function for the event $A$. In a space-time coded DS-CDMA system, IAI between the $l$th and $l'$th transmit antenna occurs if there exists at least one pair of arrival time delays $(\tau_m^l, \tau_m^{l'})$, $l \neq l'$, such that $\tau_m^l - \tau_m^{l'} \neq i \cdot T_s$ for all integer $i$. For convenience, suppose that the arrival time delay is given by $\tau_m^l = d_m^{l}T_c$ for some integer $d_m^{l} \in [0, N-1]$. Then the received signal vector $r_{m,l}(i)$ synchronized with $\tau_m^l$ is given by

$$r_{m,l}(i) = \sqrt{E_s} \sum_{j=1}^L h_m^j(i) \sum_{k=1}^K \{ x_k^j(i-1)\mathbf{a}_k^{d_m^{l}} - d_m^{l} - N + x_k^j(i)\mathbf{a}_k^{N+d_m^{l}-d_m^{l}} \} + n_m(i) \quad (4)$$

where $n_m(i)$ is a noise vector having $N$ components which are independent zero-mean complex Gaussian random variables with the variance of $N_0/2$ for each of real and imaginary parts. The received signal vector is despread by the signature sequence of the desired user to make a despread signal for the $l$th transmit antenna, $y_m,l(i)$, which is summed to obtain a combined despread signal. Without loss of generality, suppose that the first user is the desired user and $\gamma_k^l$ is the cross-correlation between $\mathbf{a}_k^d$ and $a_1$. Then the combined despread signal at the $m$th receive antenna is given by

$$y_m(i) = \sum_{l=1}^L y_m,l(i) = \sum_{l=1}^L \mathbf{a}_m^T \mathbf{r}_{m,l}(i)$$

$$= \sqrt{E_s} \sum_{l=1}^L h_m^l(i)x_k^l(i) + \sqrt{L}\eta_m(i)$$

$$+ \sqrt{E_s} \sum_{l=1}^L h_m^l(i) \sum_{k=1}^K \{ x_k^l(i)\gamma_k^{d_m^{l}} - d_m^{l} - N + x_k^l(i+1)\gamma_k^{N+d_m^{l}-d_m^{l}} \}$$

$$= \chi_m(\mathbf{x}_1(i)) + \eta_m(i) \quad (5)$$

where $\chi_m(\mathbf{x}_1(i))$ and $\eta_m(i)$ are the desired signal and the interference-plus-noise which are given by

$$\chi_m(\mathbf{x}_1(i)) = \sqrt{E_s} \sum_{l=1}^L h_m^l(i)x_k^l(i) \quad (6a)$$

and

$$\eta_m(i) = \sqrt{E_s} \sum_{l=1}^L h_m^l(i) \sum_{j=1}^K \{ x_k^j(i)\gamma_k^{d_m^{l}} - d_m^{l} - N + x_k^j(i+1)\gamma_k^{N+d_m^{l}-d_m^{l}} \}$$

$$+ \sqrt{L}\eta_m'(i), \quad (6b)$$

respectively, and $\sqrt{L}\eta_m'(i)$ is an AWGN which is modeled after the sum of $L$ Gaussian random variables with the variance of $N_0$. If the arrival times from transmit antennas are same and the signature sequences are orthogonal to each other, space-time decoding for a DS-CDMA system becomes equivalent to that for a single user system and the space-time coded DS-CDMA system has the same performance as that of the single user system. Otherwise, as the effect of inter-antenna interference, multiple-access interference, and inter-symbol interference is not negligible in (6b), only the space-time decoding degrades the system performance severely and an interference cancellation scheme is applied to the space-time coded DS-CDMA system.

3. Joint AIC and ML Decoder Scheme

Figure 2 shows the block diagram of the adaptive inter-
erreverence canceller (AIC) bank and ML decoder for the kth user. The AIC is a transversal-type filter which consists of weight-taps and delay-taps as many as processing gain of the system. In the AIC, the received signal vector is despread by a tap-weight vector instead of the signature sequence. The tap-weight vector is initially set to the signature sequence of the first user and of the signature sequence. The tap-weight vector is updated once every symbol by the complex LMS algorithm in a decision-directed mode without a training sequence [3]–[5]. The despread signal for the mth receive antenna at the ith symbol time is given by

\[ y_m(i) = \sum_{l=1}^{L} y_{m,l}(i) = \sum_{l=1}^{L} w_{m,l}^H(i)r_{m,l}(i) \]  

where \( w_{m,l}(i) \) is the tap-weight vector of the AIC for the lth transmit antenna and \( H \) stands for conjugate transposition. Based on the MMSE criterion, the tap-weight vector is adapted for minimizing the squared error signal, \( |\varepsilon_m(i)|^2 = |\chi_m(\hat{x}_k(i)) - y_m(i)|^2 \), where \( \hat{x}_k(i) \) is an estimated codeword [5], [6].

As the estimated codeword is obtained from the ML decoder after space-time decoding, the AIC in front of the ML decoder can’t use the estimated codeword to calculate the error signal before space-time decoding. Also, as the desired signal in (6a) is sum of the L coded symbols each of which is multiplied by its channel gain, it is difficult to estimate the codeword by inserting a simple slicer between the AIC and ML decoder. To obtain the error signal during space-time decoding in the AIC, a joint AIC and ML decoder scheme is proposed, in which the error signal from the ML decoder is fed back to the AIC by every symbol time. Consider ML decoding for the space-time coded DS-CDMA system. Assume that the interference-plus-noise \( y_m(i) \) has Gaussian distribution by the law of large numbers. Then, ML decoding to becomes finding \( \hat{x}_k \) which minimizes the sum of the Euclidean distance between the despread signal and desired signal as follows.

\[
\max_{\hat{x}_k} \prod_{m=1}^{M} p(r_m|\hat{x}_k) = \min_{\hat{x}_k} \sum_{i=0}^{F-1} \sum_{m=1}^{M} |y_m(i) - \chi_m(\hat{x}_k(i))|^2
\]

where \( \hat{x}_k = (x_k(0), x_k(1), \ldots, x_k(F-1)) \) is the transmitted sequence of the kth user in a frame. The branch metric corresponding to the branch from the state \( s_i \) to the state \( s_{i+1} \) is given by

\[
\Delta(s_{i+1}|s_i) = \sum_{m=1}^{M} |\chi_m(x_{k}(i)) - y_m(i)|^2
\]  

where \( \varepsilon_m(s_{i+1}|s_i) = \chi_m(x_{k}(i)) - y_m(i) \) which is the Euclidean distance between the desired signal and despread signal for the mth receive antenna and \( x_{k}(i) \) is the codeword corresponding to the branch from the state \( s_i \) to the state \( s_{i+1} \). By substituting the error signal in the LMS algorithm by the Euclidean distance of the branch metric in ML decoding, adaptive interference cancellation and ML decoding are simultaneously performed in the proposed scheme. The joint algorithm for the joint AIC and ML decoder is formulated as follows.

For the ith symbol, \( i = 0, 1, \cdots, F-1 \)

For each state \( s_{i+1} \)

For each state \( s_i \) coming into the state \( s_{i+1} \)

Compute \( M(s_{i+1}|s_i) = M(s_i) + \Delta(s_{i+1}|s_i) \).

End

Find \( \hat{s}_i = \arg \min_{s_i} M(s_{i+1}|s_i) \).

Compute \( M(s_{i+1}) = M(s_i) + \Delta(s_{i+1}|\hat{s}_i) \), and Store \( M(s_{i+1}), \hat{s}_i, \varepsilon_m(s_{i+1}|\hat{s}_i) \) in memory.

End

Find \( \hat{s}_{i+1} = \arg \min_{s_{i+1}} M(s_{i+1}) \).

Read \( \varepsilon_m(i) \equiv \varepsilon_m(s_{i+1}|\hat{s}_i) \) from memory, and Update tap-weight vector for the \( (i+1) \)th symbol.

End

where \( M(s_{i+1}|s_i) \) is a path metric including the branch from the state \( s_i \) to the state \( s_{i+1} \) and \( \sim \) stands for the selected value to minimize the path metric. The tap-weight vector for the \( l \)th AIC of the \( m \)th receive antenna at the \( (i+1) \)th symbol time is given by

\[
w_{m,l}(i+1) = w_{m,l}(i) + \mu \varepsilon_m^*(i)r_{m,l}(i),
\]  

subject to \(|w_{m,l}(i+1)a_1| = 1\), where \( * \) stands for conjugate and \( \mu \) is the step-size of the LMS algorithm. The error signal in the proposed scheme is obtained not by calculating \( \varepsilon_m(i) = \chi_m(\hat{x}_1(i)) - y_m(i) \) from the estimated codeword but by reading the selected Euclidean distance from the memory of the decoder. By obtaining the reliable error signal in ML decoding, the proposed scheme achieves better performance without much increase of complexity and processing delay.
4. Simulation Results

The performance of the proposed scheme is evaluated in the downlink of the space-time coded DS-CDMA system with two transmit antennas to each of which equal transmit power is assigned. Assume that the receiver makes perfect estimation on the channel gain and relative arrival time delay for each of the transmit antennas. In simulation the signature sequence is randomly selected among the family of the Gold sequences of length \( N = 31 \) for each user and the frame has the information data of 260 bits including padding bits which are encoded by the Tarokh’s QPSK space-time code with 8 and 16 states for two transmit antennas [1]. Assume that each of channels between transmit and receive antennas has i.i.d. Rayleigh fading with relative arrival delay \( \tau_{lm} \in [0, 10T_c] \) and \( f_DT_f = 0.001 \) where relative arrival delay is uniformly distributed with probability density function of \( f_T(\tau_m) = 1/10T_c \) and average rms delay spread of \((5/3)T_c\). \( f_D \) is the maximum Doppler frequency, and \( T_f \) is frame duration. The step-size \( \mu \) of the LMS algorithm is set to be 0.05.

Figure 3 shows the BER of the space-time coded DS-CDMA system with \( L = 2 \) and \( M = 1, 2 \), for the conventional ML decoding scheme (ML) and the proposed joint scheme (AIC+ML) in a Rayleigh fading channel. In Fig.3(a), the curve of \( K = 1 \), as a reference curve for a single user environment, shows the BER of the case where only the IAI exists without MAI. There is no improvement of performance of the proposed scheme since its performance is affected mainly by the noise than by the interference in a range of low \( E_b/N_0 \). Even if \( E_b/N_0 \) has increased, it shows only a little improvement since the amount of interference itself, to be reduced, is not large. The curve of \( K = 10 \) shows the BER of the case with MAI as much as a system reaches to the state of saturation. In this case, the performance of the proposed scheme appears to be same as that of ML because MAI beyond capacity of the system makes the initial decision of the AIC unreliable and the unreliability of the reference signal obstruct the AIC to work properly. However the performance improves little by little since its reliability increases as \( E_b/N_0 \) increases. The curve of \( K = 5 \), as an example curve for the multiuser environment that does not exceed the capacity of the system, shows that the proposed scheme achieves better performance than the conventional ML decoding scheme for the same number of users in a Rayleigh fading channel having arrival time difference.

Figure 3(b) shows that the performance improvement becomes more significant as the numbers of states and receive antennas increase. It is because the performance of the code itself improves as the number of states increases and the antenna diversity gain increases as the number of receive antennas increases. This performance improvement is achieved in the conventional ML scheme as well as in the proposed scheme. Nevertheless the reason that the amount of improvement is larger in the proposed scheme is because the effect of interference reduction of the AIC becomes larger as the reliability of the reference signal for the AIC increases.

5. Conclusions

In this letter, the joint AIC and ML decoder scheme is proposed for the space-time coded DS-CDMA system with arrival time difference. The proposed scheme performs both interference cancellation and space-time decoding by substituting the error signal of the LMS algorithm by the Euclidean distance of the branch metric in ML decoding. The performance of the proposed
scheme is evaluated in the space-time trellis coded DS-CDMA system with two transmit antennas. It is shown that the proposed scheme achieves significant improvement of performance over the conventional ML decoding scheme in a Rayleigh fading channel with arrival time difference.

References


