A MULTISTAGE MULTI-CARRIER CDMA RECEIVER WITH BLIND ADAPTIVE MAI SUPPRESSION

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ABSTRACT

A multistage multicarrier CDMA (MSMC-CDMA) receiver with enhanced multiple access interference (MAI) suppression is proposed for a reverse link time-multiplexed pilot symbols assisted system over multipath channels. The design of the receiver involves the following procedure. First, a blind adaptive matched filter is attached to each finger to perform despreading and combat MAI. Second, channel estimation and a RAKE combiner gives the estimate of the signal. Finally, signal reconstruction is accomplished by exploiting the channel estimate, data decisions, and signal's signature. The reconstructed signal is then subtracted from the data sent to the next stage. With signal reconstruction and subtraction as stages proceed, the MSMC-CDMA receiver can achieve nearly the performance of the optimal maximum SINR (MSINR) receiver, as confirmed by simulations.

1. INTRODUCTION

The direct sequence CDMA air interface has been selected to be a major candidate for providing multimedia services in the third generation mobile radio communications. This is mainly due to its soft multiple access characteristics, robustness against fading, and anti-interference capability. Recently, a new CDMA technology has been proposed based on the combination of CDMA and multi-carrier (MC) transmission to support high data rate transmission [1]. The multi-carrier based CDMA systems can be roughly categorized into two types: One is a combination of orthogonal frequency division multiplexing (OFDM) and CDMA, and the other is a scheme of parallel transmission of narrowband DS waveforms in the frequency domain [1]. In the former system (referred to as MC-CDMA), a spreading sequence of length M is serial-to-parallel converted, and then each chip modulates a different carrier frequency. This implies that the resulting signal has a spreading sequence in the frequency domain. In the latter system (referred to as MC DS-CDMA), the available frequency spectrum is divided into M equi-width frequency bands, or carriers. Each frequency band is used to transmit a narrowband DS waveform, which means that the spreading operation is done in the time domain. Both of these two types of schemes can offer frequency diversity and robustness to the adverse effect of frequency selective fading. In addition to multipath effects, an MC CDMA system is also subject to limiting factors such as multiple access interference (MAI) and narrowband interference (NBI). In forward link synchronous transmission with good channel conditions, MAI can be eliminated by employing orthogonal spreading codes. However, this is typically not achievable in reverse link asynchronous transmission or under poor channel conditions, where orthogonality among spreading codes no longer holds.

In order to effectively combat the interference, a CDMA receiver should be able to perform adaptive processing at the chip or symbol level [2]. To this end, a novel multistage adaptive receiver is proposed for MC-CDMA systems. The development of the receiver involves the following procedure. First, a set of adaptive matched filters is constructed to collect multipath signals with different time delays. The tap weights of each matched filter are determined in accordance with the linearly constrained minimum variance (LCMV) [3] criterion so that strong MAI can be effectively suppressed. In particular, these LCMV matched filters are implemented in the form of generalized sidelobe canceller (GSC) [3], and a modified blocking matrix is designed to remove the signal from the received data. Second, channel estimation and a RAKE combiner, which are combined to capture the resolvable signal multipath components coherently, gives the estimate of the signal sample. Finally, signal waveform reconstruction is accomplished by exploiting the channel estimate, symbol decisions, and signal's signature. The reconstructed signal waveform is then subtracted from the data sent to the next stage. Due to signal subtraction preprocessing, the performance of the adaptive matched filters can be significantly improved, leading to better channel estimation and RAKE combining in the subsequent stages. The proposed receiver subtracts the estimated signal before MAI suppression in an attempt to avoid the signal cancellation phenomenon often occurring in LCMV receivers [3]. This is opposite to the successive interference cancellation (SIC) or parallel interference cancellation (PIC) schemes [4], which estimate and subtract MAI. Adaptive MAI suppression is performed blindly in that the GSC does not need the signal's channel information. By simulations, it is shown that the proposed receiver is reliable and can provide nearly the performance of the optimal maximum SINR (MSINR) receiver [5] as stages proceed.

2. DATA MODEL FOR MC-CDMA

Suppose that there are K active users in an MC-CDMA system. Each user is assigned a unique spreading code in the frequency

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domain such that the complex lowpass equivalent transmitted signal of the kth user for the ith data symbol can be written as

$$s_{k,i}(t) = 1/\sqrt{T_b} \sum_{m=0}^{M-1} c_k(m) d_k(i) \exp\{j2\pi \frac{m}{T_b} t\} \quad (1)$$

where $t \in [iT_b, (i+1)T_b]$, T_b is the symbol duration, $c_k(m)$ is the spreading code, $d_k(i)$ is the ith data symbol, and M is the number of sub-carriers. The transmission channel is modeled as with L_k resolvable Rayleigh fading paths, and a guard time of T_G is inserted after $s_{k,i}(t)$ to reduce inter-symbol interference (ISI). The received baseband data can be expressed as:

$$\begin{aligned}\bar{x}(t) &= \sum_{k=1}^{K} \sum_{l=1}^{L_k} \sum_{i=-\infty}^{\infty} \alpha_{k,l} \\ &\quad \times \tilde{s}_{k,i}(t - i(T_b + T_G) - \tau_{k,l} T_c) + \bar{n}(t) \quad (2)\end{aligned}$$

where $\tilde{s}_{k,i}(t)$ is the kth user's transmitted signal after guard time insertion, and $T_c = \frac{T_b}{M}$ is the chip duration. $\tau_{k,l}$ and $\alpha_{k,l}$ are the delay and complex path gain of the lth path of the kth user, respectively. $\bar{n}(t)$ is the AWGN vector with the power σ_n^2. After removing the guard time, the received data is sampled at $t = (i-1)T_b + nT_c + \frac{T_c}{2}$ over the ith symbol duration, yielding the discrete-time data samples:

$$\bar{x}_i(n) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \alpha_{k,l} s_{k,i}(n - \tau_{k,l}) + \bar{n}(n) \quad (3)$$

for $n = 0, 1, \ldots, M-1$. After taking FFT (post-FFT), the received data in the frequency domain is given by

$$x_i(m) = \text{FFT}\{\bar{x}_i(n)\} = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \alpha_{k,l} c_{k,l}(m) d_k(i) + n(m) \quad (4)$$

for $m = 0, 1, \ldots, M-1$, where

$$c_{k,l}(m) = c_k(m) \exp\{-j(2\pi \frac{m}{M} \tau_{k,l})\} \quad (5)$$

and $n(m)$ is the FFT of $\bar{n}(n)$. Assuming user 1 to be the desired user, the received data for the ith symbol in the frequency domain can be put into the $M \times 1$ vector:

$$\begin{aligned}\mathbf{x}(i) &= [x_i(0), x_i(1), \cdots, x_i(M-1)]^T \\ &= \sum_{l=1}^{L_1} \alpha_{1,l} \mathbf{c}_{1,l} d_1(i) + \mathbf{i}(i) + \mathbf{n}(i) \quad (6)\end{aligned}$$

where $\mathbf{i}(i)$ is the interference vector, $\mathbf{n}(i)$ is the noise vector, and T denotes the transpose. Note that $\mathbf{c}_{1,l}$ is the post-FFT signature vector associated with the lth path of user 1, having the form

$$\mathbf{c}_{1,l} = [c_{1,l}(0), c_{1,l}(1), \cdots, c_{1,l}(M-1)]^T \quad (7)$$

From (6), the post-FFT signature vector of user 1 is given by

$$\mathbf{h}_1 = \sum_{l=1}^{L_1} \alpha_{1,l} \mathbf{c}_{1,l} \quad (8)$$

With the data model in (6)-(8), it is clear that a receiver for user 1 is one designed to identify and remove $\mathbf{h}_1$ to retrieve the data symbol $d_1(i)$. In order to achieve the optimal performance, $\mathbf{i}(i)$ and $\mathbf{n}(i)$ should be suppressed as much as possible. For example, the MSINR receiver [5] is the optimum linear combiner that combines the entries of the post-FFT data vector $\mathbf{x}(i)$ into an estimate of $d_1(i)$, i.e.

$$\hat{d}_1(i) = dec\{\hat{\mathbf{q}}_1^H \mathbf{x}(i)\} \quad (9)$$

where $\hat{\mathbf{q}}_1$ is the combining weight vector, $dec\{\cdot\}$ is the decision operator, and H denotes the conjugate transpose. The weight vector is chosen in accordance with [5]:

$$\hat{\mathbf{q}}_1 = \mathbf{R}_{in}^{-1} \mathbf{h}_1 \quad (10)$$

where $\mathbf{R}_{in}$ is the post-FFT interference-plus-noise correlation matrix. The use of $\mathbf{R}_{in}$ has the advantage of improved output SINR performance as compared to the use of data correlation matrix including the signal component. With the signal component removed before weight computation, the adverse signal cancellation phenomenon often occurring in LCMV receivers can be avoided [3]. However, the MSINR receiver is ideal in that $\mathbf{R}_{in}$ is not available directly from the data. In the next section, a multi-stage (MS) receiver structure will be proposed which approaches the optimal MSINR receiver in an successive fashion via signal reconstruction and subtraction.

3. DEVELOPMENT OF MSMC-CDMA RECEIVER

An MSMC-CDMA receiver is developed via the following procedure. First, a blind adaptive matched filter is designed for each finger which transforms $\mathbf{x}(i)$ from chip domain to symbol domain and performs MAI suppression. Second, channel estimation and a RAKE combiner gives the estimate of the signal sample. Finally, signal waveform reconstruction is accomplished by exploiting the channel estimate, symbol decisions, and signal's signature. The reconstructed signal waveform is then subtracted from the data sent to the next stage to obtain an estimate $\mathbf{R}_{in}$. The overall schematic diagram of the proposed receiver is depicted in Figure 1.

3.1. Blind Adaptive Matched Filters

In designing adaptive matched filters, it is convenient to treat the post-FFT signature vector $\mathbf{c}_{1,l}$ as a steering vector used in spatial array processing. In this way, an adaptive matched filter is simply a time domain analogy of a beamformer, and the beamforming concept can be readily applied. According to this, the matched filter output data at the lth finger is given by

$$\hat{y}_{1,l}^{(j)}(i) = \mathbf{w}_{1,l}^{(j)H} \mathbf{x}^{(j)}(i) \quad (11)$$

where $\mathbf{w}_{1,l}^{(j)}$ is the weight vector of the matched filter at the jth stage for the lth finger of user 1, and $\mathbf{x}^{(j)}(i)$ is the $M \times 1$ input data vector at the jth stage. Note that, as depicted in Figures 1 and 2, the 1st stage received data $\mathbf{x}^{(1)}(i)$ is the same as the post-FFT data $\mathbf{x}(i)$. To ensure an effective suppression of MAI, adaptive cancellation is performed for each of the matched filters. This is done by choosing the filter weight vectors in accordance with the LCMV criterion [3]:

$$\min_{\mathbf{w}_{1,l}^{(j)}} \quad \mathbf{w}_{1,l}^{(j)H} \mathbf{R}_x^{(j)} \mathbf{w}_{1,l}^{(j)}$$

$$\text{subject to:} \quad \mathbf{w}_{1,l}^{(j)H} \mathbf{c}_{1,l} = 1 \quad (12)$$

for $l = 1, \ldots, L_1$, where $\mathbf{R}_x^{(j)} = E\{\mathbf{x}^{(j)}(i)\mathbf{x}^{(j)^H}(i)\}$ is the received data correlation matrix at the jth stage.

In LCMV processing, the adverse phenomenon of signal cancellation usually occurs due to the mismatch of signature vectors. With such mismatch present, the signal can be treated as interference and receive a very small gain. An effective solution proposed herein is to employ the scheme of GSC [3], which is essentially an indirect but simpler implementation of the LCMV algorithm. The concept of GSC is to decompose the weight vector into two orthogonal components: $\mathbf{w}_{1,l}^{(j)} = \mathbf{c}_{1,l} - \mathbf{B}\mathbf{u}_{1,l}^{(j)}$, which lie in the range and null space of the constraint in (12), respectively. The matrix $\mathbf{B}$ is a pre-designed "signal blocking" matrix which removes user 1's signal before matched filtering. The goal is then to choose the adaptive weight vector $\mathbf{u}_{1,l}^{(j)}$ to cancel the MAI. To apply the GSC in constructing the matched filter bank, some modifications should be made. First, instead of blocking signals with a specific delay, the blocking matrix must block signals from the entire delay spread. Second, instead of using a different blocking matrix for each matched filter, the same $\mathbf{B}$ is shared by all of the L_1 fingers at each stage. Following the standard procedure of GSC, the adaptive weight vectors are determined by the following MMSE problem:

$$\min_{\mathbf{u}_{1,l}^{(j)}} \quad E\{|\mathbf{c}_{1,l}^H \mathbf{x}^{(j)}(i) - \mathbf{u}_{1,l}^{(j)^H} \mathbf{B}^H \mathbf{x}^{(j)}(i)|^2\} \qquad (13)$$

Solving for $\mathbf{u}_{1,l}^{(j)}$ yields the matched filter weight vectors

$$\mathbf{w}_{1,l}^{(j)} = [\mathbf{I} - \mathbf{B}(\mathbf{B}^H \mathbf{R}_x^{(j)} \mathbf{B})^{-1} \mathbf{B}^H \mathbf{R}_x^{(j)}] \mathbf{c}_{1,l} \qquad (14)$$

The signal blocking matrix $\mathbf{B}$ can be chosen to be a full rank $M \times (M - L_1)$ matrix whose columns are orthogonal to the set of signature vectors $\{\mathbf{c}_{1,l}, \mathbf{c}_{1,l}, \cdots, \mathbf{c}_{1,l}\}$. In case where M is large, partially adaptive techniques can be employed to reduce the size of $\mathbf{B}$ and the required computational complexity [3]. Although the blind GSC structure is easy to implement, it usually exhibits poor convergence and/or low output SINR compared to the non-blind (pilot symbol assisted) approaches. This motivates the following scheme for improving performance.

3.2. Signal Reconstruction/Subtraction and Multi-Stage GSC

Although the MAI can be effectively suppressed by adaptive matched filters, there is usually some performance degradation due to finite data samples. However, with signal reconstruction and subtraction incorporated, as illustrated in Finger 1, the proposed receiver can achieve nearly the performance of the optimal MSINR receiver.

First, as shown at the jth stage in Figure 2, the matched filter weight vector $\mathbf{w}_{1,l}^{(j)}$ is used to despread the original post-FFT data:

$$\tilde{y}_{1,l}^{(j)}(i) = \mathbf{w}_{1,l}^{(j)^H} \mathbf{x}(i) \qquad (15)$$

where $\mathbf{w}_{1,l}^{(j)}$ is estimated by (14). With $\hat{y}_{1,l}^{(j)}(i)$ and $\tilde{y}_{1,l}^{(j)}(i)$ available, channel estimates can be obtained using a sequence of N_p pilot symbols. In particular, two different channel estimates are needed. One is for the jth stage input data $\mathbf{x}^{(j)}(i)$, and the other is for the original input data $\mathbf{x}(i)$:

$$\hat{p}_{1,l}^{(j)} = \frac{1}{N_p} \sum_{i=1}^{N_p} \hat{y}_{1,l}^{(j)}(i) \qquad (16)$$

$$\tilde{p}_{1,l}^{(j)} = \frac{1}{N_p} \sum_{i=1}^{N_p} \tilde{y}_{1,l}^{(j)}(i) \qquad (17)$$

where $\tilde{y}_{1,l}^{(1)}(i)$ and $\tilde{p}_{1,l}^{(1)}$ are the same as those at the 1th stage. Note that $\hat{p}_{1,l}^{(j)}$ is used for signal reconstruction, and $\tilde{p}_{1,l}^{(j)}$ is for signal symbol detection. Using the original channel estimate $\tilde{p}_{1,l}^{(j)}$, the random phase of the lth finger output $\tilde{y}_{1,l}^{(j)}(i)$ is removed and coherent RAKE combining is achieved by

$$\tilde{z}_1^{(j)}(i) = \sum_{l=1}^{L_1} \tilde{p}_{1,l}^{(j)^*} \tilde{y}_{1,l}^{(j)}(i) \qquad (18)$$

which is then sent to the data decision device yielding

$$\tilde{d}_1^{(j)}(i) = dec\{\tilde{z}_1^{(j)}(i)\} \qquad (19)$$

Second, signal reconstruction is accomplished by exploiting the channel estimate $\hat{p}_{1,l}^{(j)}$, post-FFT signature $\mathbf{c}_{1,l}$ and symbol decision $\tilde{d}_1^{(j)}(i)$ as follows:

$$\hat{\mathbf{s}}_1^{(j)}(i) = \tilde{d}_1^{(j)}(i) \sum_{l=1}^{L_1} \hat{p}_{1,l}^{(j)} \mathbf{c}_{1,l} \qquad (20)$$

Finally, the reconstructed signal is subtracted from the data sent to the next stage. This leads to the residual data given by

$$\mathbf{x}^{(j+1)}(i) = \mathbf{x}^{(j)}(i) - \hat{\mathbf{s}}_1^{(j)}(i) \qquad (21)$$

As stages proceed, $\mathbf{x}^{(j+1)}(i)$ will contain only the MAI and noise, and $\tilde{d}_1^{(j)}(i)$ will approach the true signal symbols. Due to signal subtraction, the receiver will act like the optimal MSINR receiver operating on $\mathbf{R}_{in}$, which offers the best comprise between MAI plus noise suppression and signal reception. It is noteworthy, as shown in Figure 1, that the proposed MSMC-CDMA receiver is modularized, and in typical scenarios the number of stages required is small (3-4), making it simple and practical to implement.

4. COMPUTER SIMULATIONS

Simulation results are demonstrated to confirm the performance of the proposed receiver. For all users, $L_k = 3$ paths were generated with the delays $\tau_{k,l}$'s chosen from $\{0, T_c, 2T_c\}$, which is smaller than the guard interval $T_G = 10T_c$. The number of sub-carriers M is chosen to be 32. All CDMA signals were generated with BPSK data modulation and spread with the orthogonal Gold code. Also, the input SNR is defined to be the ratio of the signal power to noise power and the signal-to-MAI-ratio (SIR) is the ratio of the signal power to MAI power before despreading. As a performance index, the output SINR is defined to be the ratio of the signal power to the interference-plus-noise power at the receiver output $\tilde{z}_1^{(j)}(i)$. For comparison, the results obtained with the optimal MSINR receiver are also included. The MSINR receiver was implemented by artificially removing the signal component in computing the matched filter weights, in contrast to the signal subtraction procedure used in the proposed receiver. Finally, in each simulation, the input SNR was 0 dB, SIR was -20 dB, the pilot to data symbol ratio was 1/8, and a total of 1000 independent trials were executed to obtain the output SINR.

In the first set of simulations, the output SINR performance is evaluated as a function of received symbol size (N_s) (including data and pilot symbols). The results given in Figure 3 show that with strong MAI and 20 users ($K = 20$), the proposed receiver successively improves as stages proceed, approaching the MSINR receiver within about 200 received symbols. In the second set of simulations, the system capacity is evaluated with $N_s = 200$. As shown in Figure 4, the proposed receiver again successively approaches the MSINR receiver, with a degradation of only about 0.1 dB in output SINR with $K = 25$. The simulation results confirm that the proposed receiver is able to offer the performance of the optimal MSINR receiver with a moderate symbol size in the presence of a large number of multi-access users.

5. CONCLUSION

A multistage receiver is proposed for MC-CDMA communications in a multipath channel. It is designed in accordance with the following procedure. First, temporal processors are constructed as blind adaptive matched filters to suppress MAI. Second, channel estimation and a RAKE combiner gives the estimate of the signal. Finally, the signal is reconstructed in a decision-directed fashion and subtracted from the data sent to the next stage in order to obtain the signal free data correlation matrix. From simulation results, the proposed receiver is shown to be able to achieve the performance of the optimal MSINR receiver as stages proceed. The proposed receiver is modularized, and in typical scenarios, the number of stages required is small, making it simple to implement.

6. REFERENCES

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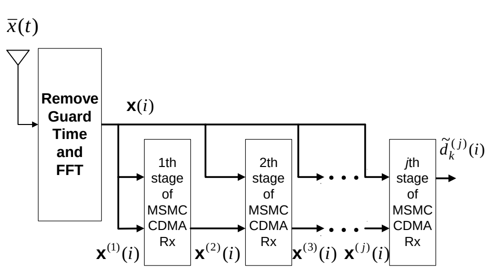

Fig. 1. Structure of proposed multistage multicarrier-CDMA (MSMC-CDMA) receiver

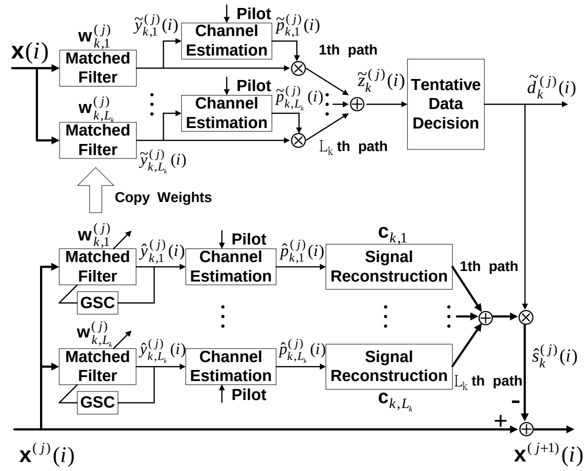

Fig. 2. The jth stage of proposed MSMC-CDMA receiver

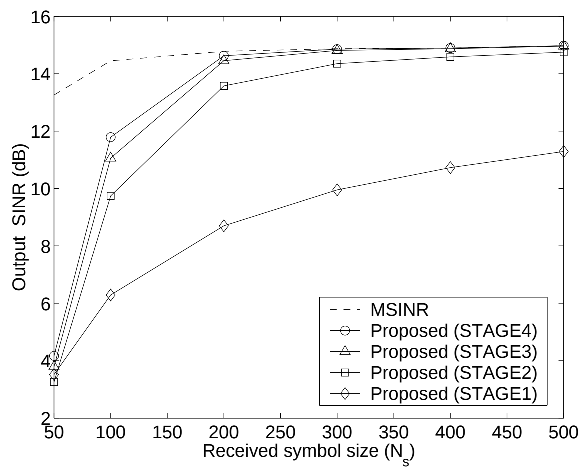

Fig. 3. Output SINR versus received symbol size N_s with $K = 20$

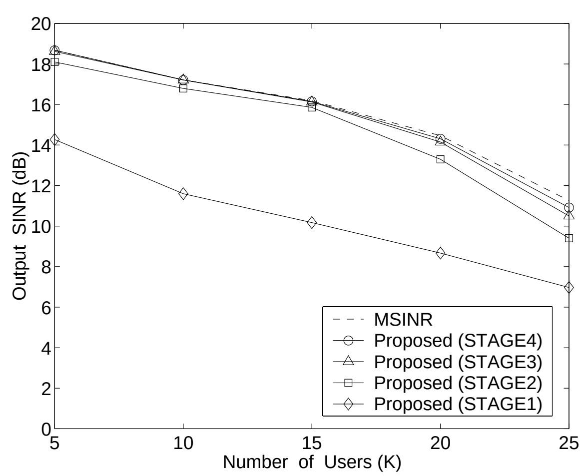

Fig. 4. Output SINR versus user number K with $N_s = 200$