A Blind Adaptive Kalman-SIC MUD Algorithm of the Wireless Multiple Access Mobile Communication System

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Abstract—The multi-user detection precision of successive interference cancellation (SIC) detector is always affected by the decision error diffusion. This paper focuses on the SIC algorithm of direct sequence spread spectrum code division multiple access (DS-CDMA) system with strong multiple access interference (MAI) and inter symbol interference (ISI). A blind adaptive Kalman-SIC multi-user detection (MUD) algorithm is proposed in this paper. This algorithm can totally track the time-varying channel, minimize the detection error diffusion, and thus effectively suppress MAI and ISI. Simulation results show that the blind adaptive Kalman-SIC algorithm is of better tracking ability, convergence and detection precision.

Index Terms—Successive interference cancellation, Kalman, DS-CDMA, multiple access interference.

I. INTRODUCTION

In the modern wireless mobile communication field, the multiple access system as direct sequence spread spectrum code division multiple access (DS-CDMA) is a popular wireless communication technology [1]. The conventional interference cancellation detector for the DS-CDMA system, as the matched filter (MF) detector, may often cause problem such as multiple access interference (MAI) which seriously restrict the capacity and performance of the DS-CDMA systems [2]. To solve this problem, in the field of multi-user detection (MUD), the successive interference cancellation (SIC) technology always has been the focus of research. Among many multi-user detectors, SIC detector and adaptive Kalman detector are good of low processing complexity and other great performances.

The SIC detector gradually reduces the maximum power user-generated interference by the multi-user data judgment of all users, estimates the user signal source of each detection level, and finally, restructures the load information of each received user signal at the receiving terminal by the signal source estimation results [3]. Because this program must constantly order the new succession sort of multi-user to priority process the maximum power user [4], so any detection error on any detection level would increase MAI and lead detection error diffusion, then severely affect the precision of the subsequent levels [5]. As an optimal estimation algorithm under the linear minimum mean square error (MMSE) criterion [6], the Kalman algorithm can not only make on-line synchronous unbiased estimation of the unknown noise statistics characteristics in DS-CDMA system while conducting state filtering, but also build a state space model for the MUD processing, so as to use optimal filter to adaptive estimate the optimal decision vector [7].

The Kalman filtering theory is one of the most important methods in dynamic data processing field [7]. The main part of this theory includes multi-variable control, optimal control, optimal estimation and adaptive control [8]. Kalman algorithm is widely used in the field of mobile communication, GPS, navigation and other dynamic monitoring for its characteristics of real-time, fast convergence, accuracy and anti-interference [9]. The problems in the 3G mobile communication field, such as MAI, inter symbol interference (ISI) and far-near problem (FNP) [10], make Kalman filtering algorithm receive more in-depth study [11]. The blind adaptive Kalman algorithm can build a state adaptive estimation of optimal decision vector [12] to estimate the unknown noise statistics characteristics on line [13], thus ensure algorithm converges to expected user. The combination of Kalman and SIC can restrain the error diffusion through the real-time estimation of channel and improve dynamic environment tracking performance.

In this paper, we present a combination of SIC and Kalman detector to restrict the generation and diffusion of detection error, and to ensure the detection precision through the real-time estimation of channel.

II. MUD MODEL FOR DS-CDMA SYSTEM

In an asynchronous DS-CDMA communication system with $2^P + 1$-length transmitted symbol, here $P$ is the user equivalent channel, and the time sequence is \{-P, ..., 0, 1, ..., P\}. Supposing the 1-user is the expected user, let K users send asynchronous signals, make spread spectrum and add additive white Gaussian noise (AWGN) for each user signal respectively [14]. Then spread spectrum secondary on chaotic sequence makes adding...
and adaptive filter processing for the spread spectrum result of each user in order, the output signal model is expressed as

$$y_k = \int_0^T r(t)s(t)dt = A_k b_k(i) + \sum_{i=1}^K A_i b_i(t) \rho_{ik} + n_k(t)$$  \hspace{1cm} (1)$$

where $A_k$ is the amplitude of the received signal, $b_k(i)$, $b_k \in \{-1, 1\}$, is the signal transmitting symbol in $t \in [IT, (i+1)IT]$. $\sum_{i=1}^K A_i b_i(t) \rho_{ik}$ is the MAI which caused by the incomplete orthogonal among user spreading codes. $n_k(t) = T^{-1} \int_0^T n(t)s_k(t)dt$ is the noise-related output of AWGN.

The traditional SIC deals MAI as noise, then detects the output of matched filter directly as $\hat{b}_k = \text{sgn}(y_k)$. This would reduce the system capacity and increase bit error rate (BER). If the energy characteristic waveform is limited to $[0, T]$, the characteristic waveform is

$$s_k(t) = \sum_{l=0}^{N-1} s_{k,l} P_{\mathcal{C}}(t-IT\mathcal{C}), \quad (P_{\mathcal{C}} = T^{-1/2}, \mathcal{T}_C = T/N)$$  \hspace{1cm} (2)$$

where $l = \{-L, L\}$, $\{s_{k,0}, s_{k,1}, \ldots, s_{k,N-1}\}$ is the normalized spectrum sequence ($\pm N^{-1/2}$), $N$ is the spread spectrum processing gain, and $P_{\mathcal{C}}$ is the $T_C$-cycle matrix code piece.

Set the system noise $e_k(t)$ of $k$-th user is equivalent to the sum of AWGN component $n_k(t)$ and colored noise $\xi_k(t)$, the sum noise of system is

$$e_k(t) = n_k(t) + h_k \xi_k(t)$$  \hspace{1cm} (3)$$

where $\xi_k(t)$ is colored noise (zero mean), $h_k$ is the colored noise intensity.

The sum sequences noise component is $e(n,i)$ ($e(n,i) = e(nL+i)$).

At the receiving terminal, the received signal after dealing with adaptive filter and binary phase shift keying (BPSK) modulation can be equivalent as follow

$$r(t) = \sum_{k=1}^K \sum_{l=-\infty}^{\infty} [A_k b_k(i)s_k(t-IT-\tau_k) + p_k(t-IT-\tau_k) \cos(\omega_{\tau_0} t)] + \sum_{k=1}^K e_k(t)$$  \hspace{1cm} (4)$$

where $p_k(\pm 1)$ is the waveform of the secondary spread spectrum, $T$ is the bit interval, $\tau_k$ is the time delay, and $\omega_{\tau_0}$ is the adaptive weight vector of filter unit.

In a DS-CDMA system, the long spread spectrum sequences cycle $L$ meets $L/N \leq Q > 1$. By replacing $s_k(t-IT-\tau_k)$ by $s_{k,(\tau_0)}(t-IT-\tau_k)$, the received signal model on Eq. (2) is

$$s_{k,(\tau_0)}(t) = \sum_{l=0}^{N-1} s_{k[l]}(t) P_{\mathcal{C}}(t-IT\mathcal{C})$$  \hspace{1cm} (5)$$

if $l \notin [-1, 0, 1]$, then $R(l) = 0$, $R(-l) = R^T(l)$.

Set the received signal sampling rate is equal to chip rate, $r$ is the output vector of $L$-dimensional match filter in symbol interval $T$. So the vector form of asynchronous DS-CDMA system base band received signal model can be formed as

$$r = \sum_{k=1}^K A_k b_k s_k p_k + e$$  \hspace{1cm} (7)$$

where $A = \text{diag}[A_1, A_2, \ldots, A_K]^T$, $p_k = L^{-1}[p_1 k, p_2 k, \ldots, p_L k]^T$, and $e$ is the zero mean sum noise covariance matrix.

$$E[ee^T] = \sigma^2 I$$

$\sigma^2$ is the noise variance, estimates the transmitted user signal bit symbol in any user signal transmission process relative interval, and

$$y = RAb + n = [y_1, y_\mathcal{C}]^T, \quad (R = E[pp^T]).$$

Set the time delay of the $k$ th user is $\tau_k$, when $\max\{\tau_k\} \leq T$, estimates the bit symbols of the transmitted user signal in any relevant transmission interval, then an asynchronous DS-CDMA system with $K$ user $s$ could be equivalent to a synchronous user DS-CDMA system with $2K-1$ users. Supposing $2K-1 \leq L$ and all spreading code of these $2K-1$ users are linearly irrelevant, then the calculation of asynchronous system is similar to the synchronization system.

### III. Kalman-SIC Algorithm

The Kalman filter can measure noise online and adaptive estimate the optimal decision vector $\mathbf{c}_k(i)$ by optimal filter [15]. In the multi-path fading channel, set the adaptive weight vector $\mathbf{a}_{\tau_0}$ of each filter unit to be the adaptive update component of $\mathbf{c}_k(i)$, $\mathbf{a}_{\text{opt}}$ is the weight vector of $\mathbf{c}_{\text{opt}}$, $g_{\text{opt}}(i)$ is the equivalent channel response, $\{\mathbf{c}_k(i)\}_{i=0}^{L-1}$ is $L$-length spread spectrum code, and $\mathbf{e}_{\text{opt}}(k)$ is sum noise vector. The process equation and observation equation of the expected user are as follows:
The dynamic system process equation and observation equation are as follows:

\[
\begin{align*}
    x(k+1) &= F(k+1,k)x(k) + e_{\text{opt}}(k) \\
    y(k) &= C(k)x(k) + e_2(k)
\end{align*}
\]  

(9)

where \(x(k)\) is the \(L\times1\)-dimensional system state vector in \(k\) moment, \(e_{\text{opt}}(k)\) is the process noise vector (\(e_{\text{opt}}(k) = 0\)), \(F(k+1,k)\) is \(L\times L\) -order state transfer matrix \(I\), \(y(k)\) is the \(Z\times1\)-dimensional system state vector in the \(k\)th moment (\(y(k) = \gamma(k)\)), \(Z = [(L+P-1)/L]\), \(C(k)\) is a \(Z\times L\) -order measurement matrix, \(e_2(k)\) is the measurement matrix error (\(e_2(k) = \hat{\varepsilon}_{\text{opt}}(k)\)), and \(C(k)\) is simplified to the \(Z-1\) -dimensional row vector \(d^T(k)\).

After through the channel fading, the spread spectrum code signal can be formed as

\[
d_k(i) = c_k(i) \ast g_k(i) = \sum_{p=0}^{P-1} g_k(p)c_k(i-p)
\]  

(10)

The \(i\)-th sampling of the received base band signal in the \(k\)-th symbol period is defined as

\[
\begin{align*}
    x(k,i) &= x(kL+i) = \sum_{k=0}^{K-1} \sum_{z=0}^{Z-1} A_k d_k(z,i) b_k(i-z) \\
    d_k(z,i) &= d_k(zL+i), d_{k-1} = (1-z)/(1-z^4), 0 < z < 1
\end{align*}
\]  

(11)

where \(z\) is the forgetting factor of corresponding vector.

The \(L\) samples in the \(k\)-th symbol periods can be represented to be a \(L \times 1\) -order matrices as

\[
x(k) = Ad_k b(k) + D_{\text{in}} d_{\text{in}}(k) + e(k)
\]  

(12)

where \(D_{\text{in}}\) is the interference matrix with ISI and MAI, \(d_{\text{in}}\) is the interfering symbol vector.

Set a \(L\) -dimensional decision vector \(f(k)\) for the expected user, then the MUD model of K-SIC detector is

\[
\hat{b}(k) = \text{sgn}(< f(k), x(k) >)
\]  

(13)

Supposing the iteration number \(n = 1,..,N\), iterative coefficient matrix satisfy the condition as \(M(1,0) = I\), so

\[
\begin{align*}
    &M(n+1,n) = M(n,n-1) - g(n) d^H(n) M(n,n-1) \\
    &g(n) = M(n,n-1) d^H(n) M(n,n-1) d(n) + \varepsilon_{\text{min}}^{-1} \\
    &\hat{\omega}_{\text{opt}}(n) = \hat{\omega}_{\text{opt}}(n-1) + g(n) \{y(n) - d^H(n) \hat{\omega}_{\text{opt}}(n-1)\} \\
    &e_{\text{opt}}(n) = S_{1} - C_{1,f} \hat{\omega}_{\text{opt}}(n)
\end{align*}
\]  

(14)

where \(\varepsilon_{\text{min}}\) is the minimum output energy, \(e_{\text{opt}}(n)\) is a zero mean measured error sum noise vector of the expected user, \(S_{1}\) is the \(S\) scale receiving signal, \(g(n)\) is the iterative calculation, \(e_{\text{opt}}(n)\) is the measurement value matrix. Set \(\varepsilon_{\text{min}}\) is the minimum mean square error, then

\[
\varepsilon_{\text{opt}} = \text{cov}(e_{\text{opt}}) = F(e_{\text{opt}}(n)) = \Lambda^{2} + \varepsilon_{\text{min}}
\]

(15)

Therefore, in this DS-CDMA system, the dynamic system equation of the expected user can be formed as

\[
\begin{align*}
    &\hat{\omega}_{1}(k) = \hat{\omega}_{1}(k-1) + \Delta \hat{\omega}_{1}(k-1) \\
    &\hat{x}(k) = F^{H}(k) \hat{\omega}_{1}(k) + \varepsilon_{1}(k)
\end{align*}
\]  

(16)

where \(\hat{x}(k)\) is the observation vector (\(\hat{x}(k) = d^H_{k} x(k)\)), \(F^{H}(k)\) is the observation matrix (\(F^{H}(k) = x^{H}(k) U_{null}\), \(U_{null}\) is the noise subspace contains the corresponding orthogonal eigenvectors), and \(\varepsilon_{1}(k)\) is the observation noise matrix (\(\varepsilon_{1}(k) = e_{\text{opt}}^{H}(k) x(k)\)).

On Eq.(15), Kalman unit is able to accurately estimate \(\hat{\omega}_{1}(k)\), which is the adaptive update part of \(e_{\text{opt}}\), then make \(\hat{\omega}_{1}(k)\) to be the tap weight vector of expected user.

Because the communication system parameters as the number of activity users in channel and noise characteristics are time-varying, so the single Kalman algorithm is easily cause divergence or filtering and low accuracy, which reduce the stability of communication system. Therefore, it is necessary to improve the iterative calculation process of adaptive Kalman filtering algorithm are as follows

\[
\begin{align*}
    &\hat{\omega}_{2}(n) = \hat{\omega}_{2}(n-1) + M(n) \delta(n) \\
    &\hat{\omega}_{2}(n) = \hat{\omega}_{2}(n-1) + q(n-1) + d_{k-1}[\hat{\omega}_{2}(n) - \hat{\omega}_{2}(n-1)] \\
    &\delta(n) = \hat{x}(n) - F^{H}(n) \hat{\omega}_{2}(n) - r(n-1) \\
    &\hat{x}(n) = d^H_{k} x(n) \\
    &M(n) = P(n-1) F(n) \quad M(n) = F^{H}(n) P(n) \\
    &P(n) = [I - M(n) F^{H}(n)] P(n-1) \\
    &r(n) = (I - d_{k-1}) r(n-1) + d_{k-1}[\hat{x}(n) - F^{H}(n) \hat{\omega}_{2}(n)] \\
    &Q(n) = (I - d_{k-1}) Q(n-1) + d_{k-1}[M(n) \delta(n)] M^{T}(n) + P(n) P(n-1) \\
    &R(n) = (I - d_{k-1}) R(n-1) + d_{k-1}[\delta(n)] M^{T}(n) + P(n) P(n-1)
\end{align*}
\]  

(17)

Because of the introduction of adaptive Kalman filtering unit, the Kalman-SIC algorithm can adaptively eliminate the unit weight and track the time-varying
channel better than Kalman algorithm. The SIC unit selects specific amplitude, delay and phase to let the corresponding sequence make secondary modulation of detected data codeword, then remove the secondary signal and subtract MAI to convert the weaker power signals as the output of the next level. Finally, restore the valid data of all users in turn[16]. The m -th detection level structure of Kalman-SIC detector is shown in Fig.1: this structure can use the relevant information of observational data to estimate the properties of time-varying unknown noise statistics real-time while conducting state filtering[17]. Set $y_k$ is the actual output vector of filter, $v(k)$ is the input vector, $u(k)$ is the energy input vector of SIC unit, $d(k)$ is the expected response vector, and $\mu$ is the step parameter, so

$$v(k) = d(k) - \omega^H(k)u(k)$$

$$\omega(k + 1) = \omega(k) + \mu u(k) \ast v(k)$$

(20)

Figure 1. The single-stage structure of Kalman-SIC detection unit

The signal output of k-user in the m-th detection level of traditional SIC detector[18] can be formed as

$$b_m(k) = \text{sign}[S^T_m v_m(k)]$$

(21)

The maximum power user is expressed as

$$r_{\text{max}}(t) = \arg \max_{m \leq k} \{|[S^T_m v_m(k)]| \}
= \arg \max_{m \leq k} \{|[s_{k,0\ldots,k-1}]v_m(k)]| \}
$$

(22)

where $S_k$ is the S band asynchronous spread spectrum code after double spread spectrum.

On the m-th (m is an integer greater than 1) level, $v_i(k) = r(t)$, the detected signal $b_{ki}(k)$ can be changed as

$$v_{m+1}(k) = v_m(k) - \omega_m(k)b_m(k)S_m(k)$$

(23)

the weight for the detector after through the adaptive Kalman filter detection unit is adjusted as:

$$\omega_m(k + 1) = \omega_m(k) + 2\mu v_{m+1}(k)b_m(k)S_m(k)$$

(24)

Estimates MAI secondary by the estimated value of $b$ on the m-th level, then twice eliminates the MAI component from output vector $y$. Finally, get the estimated value of $b$ on the $m+1$-th detection level. The detection process is terminated with no new user added.

IV. SIMULATION ANALYSIS

In a DS-CDMA system (Multi-path number $P = 10$, $K$ users), let each user sends an information symbol in multi-path channel in each simulation step(1s), then use $m$-sequences(The number of sequences is $K \cdot N = 31$) to make independent spread spectrum and add sum noise processing, while make adding processing in user's order respectively. The $K$ users send asynchronous signal in $S$ band transmission asynchronous after through double spread spectrum processing[19]. Then, use the same $K$ m-sequence to despread the information symbols. Finally, complete the symbol recovery processing of these $K$ users (the symbol number is equal to the transmission time) by the integral decision[20] at receiving terminal and sending terminal. Set the k-user as the minimum power user, every bit energy is $A_k^2 T / 2$.

Use Kalman-SIC and SIC detector to detect the excess output energy (EOE) performance of Kalman-SIC, Kalman and SIC algorithm. The k-th iterative output signal to interference ratio (SIR) performance on the m-th level of this system is defined as

$$\text{SIR} = \frac{E^2\{c_{\text{opt}}^T(n)r\}}{\text{var}\{c_{\text{opt}}^T(n)r\}}$$

$$= \frac{\sum_{k=2}^{K} A_k^2\{c_{\text{opt}}^T(n)p_k\}^2 + \sigma^2\{c_{\text{opt}}^T(n)c_{\text{opt}}(n)\}}{A_k^2\{c_{\text{opt}}^T(n)p_k\}^2}$$

(25)

A. Static Performance Comparison Analysis

Set $K$ users with different power values. Assume there are no addition and no withdrawal of existing users in the process of the whole communication. This program simulates the static mobile communication environment.

As shown in Fig. 2: Under static conditions, when the iteration number is greater than 600, the SIR performance of Kalman-SIC algorithm is significantly better than Kalman algorithm and SIC algorithm. This means the Kalman-SIC algorithm is of faster convergence rate and stronger multi-user interference inhibition ability in the static condition.

As shown in Fig. 3: When the iteration number is greater than 600, the EOE curve of Kalman-SIC algorithm is always below 0.05dB and late in the detection process has been close to the theoretical value of 0dB. The EOE curve of Kalman is always in unstable change and basically greater than 0.1dB. The EOE curve of SIC algorithm is in unstable change and always greater than 0.1dB, then it is so easier to cause detection error diffusion. This means the Kalman-SIC is of better convergence, stability and interference rejection capability in the static condition.
As shown in Fig. 4: Under static conditions, the decision error of Kalman-SIC and SIC algorithm are both stabilized, the decision error of Kalman-SIC algorithm attenuate fast and significantly lower than the same performance of SIC algorithm in the whole process. This means the Kalman-SIC algorithm is of higher detection precision, namely it can effectively inhibit the interference of strong interference in the static condition.

Figure 2. The static SIR performance analysis

Figure 3. The static EOE performance analysis

Figure 4. The static error mean square performance analysis

B. Dynamic Performance Comparison Analysis

Set initial dynamic condition is same to the static environment, add a set of users with lager power, when the iteration number is 600, withdraw these users and a part of original user when the iteration number is 1200. This program simulate the actual dynamic mobile communication environment.

As shown in Fig. 5: In the same interference background, when the iteration number is 600, namely there is new interference added in the system, the SIR curve of Kalman-SIC and Kalman algorithm just appear little bit down peak and recover fast at a high speed before the interference been receded. But the SIR curve of SIC algorithm appears a great attenuation volatility and even becomes unstable convergence after the interference is withdrawn. This means the Kalman-SIC is of better dynamic tracking performance than Kalman algorithm and SIC algorithm.

As shown in Figure 6: The EOE of SIC and Kalman algorithm have no effective convergence in the whole process, the EOE of Kalman appears a great instability fluctuations when the interference brought into the system and recover very slow at a low speed before the interference users been receded while basically higher than 0.1dB. The EOE of SIC appears serious divergence after the interference brought into the system and ultimately failed to converge. The EOE of Kalman-SIC start remarkable convergence before the interference been receded and basically lower than 0.1dB, final attenuate close to zero value theory. These mean that the Kalman-SIC is of better interference rejection capability, convergence stability and MUD ability.

As shown in Fig. 7: Under dynamic conditions, the decision error of SIC algorithm appear a great instability fluctuations and recover very slow at a low speed before the interference users been receded and basically higher than $10^{-3}$. The decision error of Kalman-SIC is basically close to $10^{-4}$, in the whole process. This means the Kalman-SIC is of higher detection precision, namely the Kalman-SIC detector can effectively inhibit the interference of strong FNP and improve the detection precision in the dynamic condition.
C. BER Performance Analysis

Use spreading sequence adapts GOLD sequence, source adapts BPSK signal, step size is $\mu = 0.0005$, the sampling rate is equal to the chip rate. The difference power value between the maximum user and the minimum user is 8dB, the BER is defined as:

$$P_k(\sigma) = Q\sqrt{e_k(\sigma)\sigma^{-2}}$$  \hspace{1cm} (26)

where: $e_k(\sigma)$ is the equivalent energy of the $k$th user.

As shown in the Fig. 8, Fig. 9: The blind adaptive Kalman-SIC is of better BER performance, namely the new detector can effectively inhibit the interference of strong FNP and improve the detection precision. These mean that Kalman-SIC is of better MAI rejection ability, and MUD ability.

V. CONCLUSION

The Kalman-SIC algorithm can adaptively determine whether to continue operation according to the latest information variables without waiting for data input at any time, while it is helpful for implementation of project. Because there is no system background noise adding in the MAI cancellation processing, the new algorithm can fully track the time-varying channel in complex condition and completely eliminate the co-channel interference. Because it is no need to sort the order of different power user in the MUD processing, so it can effective avoid detection error diffusion caused by the intermediate link detection error of traditional SIC. Simulation results show that, the Kalman-SIC algorithm outperforms the Kalman algorithm and SIC algorithm in term of BER performance, dynamic tracking capability, convergence and precision control capability. Therefore, the blind adaptive Kalman-SIC MUD algorithm is an efficient MUD scheme.

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