Abstract: This paper proposes a unique low complexity semi-blind channel estimation and data detection receiver for downlink MC-CDMA systems. In this iterative scheme, the CSI is predicted through short range wireless channel prediction algorithm initially. With the predicted CSI, the novel data detection based on PIC is employed to achieve the data decision results. The refined CSI is acquired from the decision feedback simultaneously. This process repeats multiple times until the CSI converges. With the use of QMMSE/MMSE-PMRC PIC based on CQS instead of Walsh codes, the performance of channel estimation and Multi-User Detection is improved and the system complexity is reduced at the same time. The simulation results indicate that our proposed system has a good BER performance and channel tracking ability in different channels and system loading conditions.

Keywords: Multi-carrier code division multiple access (MC-CDMA), channel prediction, channel tracking, parallel interference cancellation.

1. Introduction

Multi-carrier code division multiple access (MC-CDMA) is a multiple access scheme used in orthogonal frequency-division multiplexing (OFDM) based telecommunication systems, allowing the system to support multiple users at the same time. MC-CDMA exploits frequency diversity via different subcarriers. Therefore it allows the high code rate systems to achieve good bit error rate (BER) performances [1].

To improve the performance of MC-CDMA systems, multi-user detections (MUD) are applied. Among different MUD methods, interference cancellations (IC) are fairly promising, since they achieve a better performance than single user detection (SUD) techniques and still maintain a linear complexity in the number of users [2]. In general, the IC methods for multi-user systems are broken into two categories: parallel and successive. In a downlink MC-CDMA system, the simple and effective power control method is to transmit the signals of all users with the same power approximately. Under this circumstance, parallel interference cancellation (PIC) is definitely better than successive interference cancellation (SIC) [3]. Accordingly PIC is selected even its complexity is slightly higher than that of SIC. The concept of SIC/PIC is based on the premise that the received signal can be reliably estimated, which is not always true in a realistic communication system. As indicated in [4], there are two main limitations of SIC/PIC schemes, which are imperfect interference cancellation due to non-ideal channel estimation and error propagation caused by erroneous symbol decision feeding back.

Channel estimation is a crucial part of the receiver structure. Since it is obvious that the blind channel estimation is disadvantageous in mobile applications, the channel estimation is generally based on the use of pilot subcarriers in given positions of the frequency-time grid. To ensure adequate estimation accuracy in rapid time-variant channels, the pilot subcarriers is suggested to be placed in each OFDM symbol [5]. However, long spreading codes cannot be used to maintain the orthogonality and hence the number of maximum active users is very limited. Additionally, the effect of interpolation is not well for a rapid time-variant fading channel even a complicated interpolation method is applied.

Many receiver design frameworks need to know the noise variance and channel covariance matrix. However it is usually difficult to get their information in practice for a mobile terminal. Hence, the channel estimation and data decision results should be extracted without them.

Iterative joint data detection and channel estimation for MC-CDMA system can be found in the recent research literature. In [5] and [5], Joint Data Detection and Channel Estimation Technique for Uplink MC-CDMA Systems Based on Space-Altering Generalized Expectation–maximization (SAGE) Algorithm is discussed. The algorithm complexity makes it only suitable for uplink. A unique channel estimator was proposed by [5] for uplink MC-CDMA system where only one pilot symbol per frame was used to obtain the initial channel estimate. The assumption of highly correlated relationship between two successive channel coefficients limits its practical usage. A maximum a posteriori (MAP) Channel-Estimation-Based PIC Receiver is proposed in [5]. The system relies on some theoretical assumptions that the Channel Environment follows normal or exponential distribution and converge speed of the algorithm is relatively slow. An adaptive multistage multiuser detector for MC-CDMA communication systems using evolutionary computation Technique is presented in [5]. To the best knowledge of the authors, there is no existing work trying to eliminate MAI through the spread sequences own property, finally effectively reducing system complexity, and improving the system performance simultaneously.

In this paper, we propose a unique low complexity semi-blind channel estimation and data detection scheme for downlink MC-CDMA systems. There are two working modes in the system. They are pilot transmission (PT) mode and data
transmission (DT) mode. Periodically, the system enters the PT mode to obtain the channel side information (CSI), and then it tracks the channel variations and detects the actual data in the DT mode until the next PT mode comes. With a certain period of CSI observations obtained in the PT mode, the variation of the channel is predicted by the short range wireless channel prediction algorithm [11] in the DT mode. With the predicted CSI, the novel data detection based on PIC, minimum mean square error (MMSE) and maximal ratio combining (MRC) is employed to achieve the data decision results. The refined CSI is acquired from the decision feedback simultaneously. This process may be repeated several times until the CSI converges. The final CSI values are stored as the basis of next CSI prediction. The noise variance is estimated in the PT mode, and we assume it is unchanged during the entire DT mode period.

The contributions of the paper are listed as follows.

1. Complex Quadratic Sequences (CQS) [12] is used as our spreading sequences. Besides its constant envelope property to mitigate the Peak-to-Average Power Ratio (PAPR) in multi-carrier systems, CQS can eliminate the MAI effectively [12]. Based on CQS, a new PIC method is proposed. It is proved that only a small part of active users will interfere with the specified user. By canceling this small portion of users it is enough to get rid of all MAI in the ideal case, and the complexity is reduced significantly. Along with the decreasing of the cancelled user number, the errors brought by imperfect channel estimation and erroneous data detections are mitigated as well. It improves the interference cancellation performance and lowers the complexity at the same time.

2. In a PIC scheme, it is important that the relatively reliable interference and CSI can be obtained as its cancellation basis. The global MMSE (GMMSE) supplies good results with excessive computation effort. In the proposed system, the Combination of MMSE and GMMSE is adopted and good results are received with significantly reduced effort. Unlike GMMSE that calls for the solution of $N \times N$ linear equations, only $G \times G$ linear equations are needed to be solved, where $N$ is the maximum user number and $G$ is the fraction of the current active user number. As the system only focuses on less reliable detection data and puts less effort on more reliable detection results, the complexity is reduced greatly without loss of the performance.

3. The noise variance and channel information are not necessarily known in advance. (The noise is assumed as Gaussian Noise.) The parameters can be estimated in the PT mode, and the CSI can be effectively tracked with the short range wireless channel prediction algorithm [11] in the DT mode with low complexity. This method consumes much less bandwidth compared with traditional method.

The channel encoder and decoder are omitted for the sake of simplifying the system model. They can be added to improve the system performance further. In the proposed downlink MC-CDMA system, unlike [13] and [14], the decoder is not involved in the PIC process, since it is not feasible to implement this kind of processing on a MT due to its complexity. Under different channel and system loading conditions, the simulation results and analysis indicate that our proposed system has good BER performance and channel tracking ability.

The paper is organized as follows. Section II defines the system model and the MC-CDMA transceiver structure. The semi-blind channel estimation and data detection schemes for downlink MC-CDMA systems are detailed in this section. Simulation results and related discussions are shown in Section III. Finally the concluding remarks are given in Section IV.

2. System Description

The overview of the system model is illustrated in Figure 1. We ignore the channel encoder and decoder because they do not change the essence of the problem. The system employs $N$ sub-carriers. Every one of the user bits will be duplicated $N$
times, or synonymously, the spreading factor equals to 1. Then all the $N$ bits are spread by the CQS. The CQS has many interesting properties that will be given a brief introduction. The CQS is defined as follows.

$$g_n = e^{-\frac{\pi}{N} \frac{2\pi i n}{N^2}} / N, \quad n=0,1,...,N-1$$

(1)

$$G_k = e^{\frac{\pi}{N} \frac{2\pi i k}{N^2}} / \sqrt{N}, \quad k=0,1,...,N-1$$

where $\{ g_n \}$ and $\{ G_k \}$ are a DFT/IDFT pair, and $G_n^* = \sqrt{N} g_n$. It is noticed that both time domain sequences $\{ g_n \}$ and frequency domain sequences $\{ G_k \}$ have a constant envelope. If the modulator is $M$-PSK type, it implies the transmitted signal has a constant envelope in both time and frequency domains. Obviously this leads to a significant reduction of the peak-to-average power ratio (PAPR). Another important property that has been proved in [12] is that both the sequences $G_k$ and $g_n$ are circular auto-orthogonal. This property is very useful for multi-user detection (MUD) and for combating multi-path fading, which will be discussed later. As usual for multi-carrier systems, Guard Interval (GI) has been added to suppress Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI) after IFFT transformation. However, the parts of GI insertion will be removed in order to simplify the analysis. Furthermore, the perfect OFDM time and frequency domain synchronization have been assumed in our system. Since this is a downlink system, multiple users will send signals at the same time. Assuming there are $M$ users in the communication link and the base station (BS) transmits data until next PT mode period starts.

2.1. PT Mode

Only pilots are transmitted in the PT mode. The pilot symbol is represented as:

$$X_p = g_p G_{(256)}$$

(7)

where $g_p$ is the pilot gain for achieving more precise channel information and $G_{(256)}$ is the pilot specific spreading code. The spreading code can be chosen from the set of spreading sequences arbitrarily. The fixed value is employed only for the sake of clear illustrations. The received signal can be written as:

$$Y_p = X_p H_p + W_p$$

(8)

where $H_p = \text{diag}(H_{p,0}, H_{p,1}, H_{p,2}, ..., H_{p,N-1})$ gives the frequency domain channel attenuations and $W_p$ is the vector of uncorrelated complex frequency domain Gaussian random noise. Simple Least Square (LS) algorithm can be applied to estimate $H_p$. However, in the proposed system, the channel tracking ability highly depends on the accuracy of the results during the PT period. Hence a more advanced method is necessary and many have been proposed to improve the performance of the LS method, such as LMMSE [15], SVD based on LMMSE [16], and Low Rank [17]. The entire above are quite complicated and they all need channel autocorrelation and noise variance, which are generally unknown for a mobile terminal. In this paper, we use a very simple but effective technique to improve the system performance. First, the LS method is applied to equation (8). It is given by

$$h_{t,k} = \left( \text{diag}(X_p) \right)^{-1} Y_p$$

(9)

where $h_{t,k}$ is the LS vector result of frequency domain channel attenuations. Next, the following algorithm is performed.

1. Get the time domain CIR vector

$$h_{t,k} = \text{ifft}(h_{t,k})$$

(10)

2. Keep only the most significant elements in $h_{t,k}$, say,

$$h_{t,e} = h_{t,k}, \quad h_{t,e}(L; : N-1) = 0$$

(11)

where $L$ is the tap number of the channel.

3. Re-transform the time domain CIR $h_{t,e}$ to the frequency domain

$$H_e = \text{diag}(\text{fft}(h_{t,e}))$$

(12)

In fact, the information of tap number $L$ indicates that the majority energy of the channel is located in the part of $[0; L-1]$. Eliminating the energy beyond this part will suppress the noise greatly while preserving the channel information well. In this
step we will also estimate the noise variance in the frequency domain. After simple calculation, it is given as
\[ \sigma_w^2 = \text{var}(h_{t,k}(L \cdot N - 1)) e_p^2 / N \] (13)

In the PT Mode, the pilot symbol is necessary to be transmitted for adequate periods of time to ensure the successful channel tracking in the DT Mode. After \( S \) times’ processing, the following estimated results for the channel can be obtained.
\[ [H_{t,1}, H_{t,2}, \ldots, H_{t,S}] \] (14)

where the index signifies different symbols.

2.2. DT Mode

There is no pilot in the DT Mode. We need to crack the CSI from the received data blindly. This process is divided into two parts. They are channel tracking and data detection with decision feedback channel estimation.

A. Channel Tracking

The channel tracking problem is to find \( \hat{H}_{t,k}(S+1) \) as \( H_{t,1}, H_{t,2}, \ldots, H_{t,S} \) are known. Without losing the generality, only one diagonal element \( \hat{H}_{t,k}(S+1) \) is necessary to be considered where \( k \in [0, N-1] \) that denotes frequency domain CSI index. In this paper the short range channel prediction Error! Reference source not found. is employed to attain the current channel information based on the previous CSI observations. As shown in [18], the real part function \( I_{t,k}(t) \) and imagery part function \( Q_{t,k}(t) \) of \( H_{t,k}(t) \) can be regarded as the summation of many sinusoids. So the \( S \) order derivatives are continuous. With a function of \( S \) continuous derivatives, an \( S-I \) order polynomial can be used to approximate the function. The approximation error is determined by the following theorem [19].

Theorem: Given \( a < b \), a function \( f(x) \) with \( S \) continuous derivatives on \( [a, b] \), a polynomial \( p(x) \) with degree \( S-I \) so that
\[ p(x_i) = f(x_i) \] (15)

where \( i = 1, \ldots, S \) and the set \( x_i \in [a, b] \) \((x_1 = a \text{ and } x_S = b)\) are distinct. Then for every \( x \in [a, b] \), there exists a point \( \xi \in [a, b] \) such that
\[ f(x) - p(x) = \frac{(x-x_1) \ldots (x-x_S)}{S!} f^{(S)}(\xi) \] (16)

The approximation error can be controlled if \( \{x_i\}_{i=1}^{S} \) is chosen properly. Thus, the approximation polynomials \( \hat{I}_{t,k}(t) \) and \( \hat{Q}_{t,k}(t) \) have the local information of \( I_{t,k}(t) \) and \( Q_{t,k}(t) \), respectively. \( \hat{H}_{t,k}(S+1) \) can be easily found by extrapolating \( \hat{I}_{t,k}(t) \) and \( \hat{Q}_{t,k}(t) \) to the next sampling point. Next we describe the process of obtaining \( \hat{I}_{t,k}(S+1) \), whereas \( \hat{Q}_{t,k}(S+1) \) follows in the same way. Write \( \hat{I}_{t,k}(t) \) as the polynomial form:
\[ \hat{I}_{t,k}(t) = \sum_{i=0}^{S-1} c_i t^i \] (17)

satisfying \( \hat{I}_{t,k}(t) = I_{t,k}(t) \mid_{t=1}^{S} \). Clearly, \( c_i \) can be obtained by solving the linear equations
\[ \mathbf{B} \mathbf{c} = \mathbf{a} \] (18)

where
\[ \mathbf{c} = [c_0, c_1, \ldots, c_{S-1}]^T, \mathbf{a} = [I_{t,k}(1), I_{t,k}(2), \ldots, I_{t,k}(S)]^T \]

\[ \mathbf{B} = \begin{bmatrix}
1 & 1 & 1 & \cdots & 1 \\
1 & 2 & 2^2 & \cdots & 2^{S-1} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & S & S^2 & \cdots & S^{S-1}
\end{bmatrix} \] (19)

Therefore
\[ \mathbf{c} = \mathbf{B}^{-1} \mathbf{a} \] (20)

Based on the result of equation (17), \( \hat{I}_{t,k}(S+1) \) is:
\[ \hat{I}_{t,k}(S+1) = \sum_{i=0}^{S-1} c_i (S+1)^i \] (21)

\( \hat{H}_{t,k}(S+1) \) can be attained after getting the value of \( \hat{Q}_{t,k}(S+1) \). Now let us calculate the complexity of the channel prediction. \( \mathbf{B}^{-1} \) and (\( S+1 \)) \( \mathbf{Y} \) should be calculated offline. Equation (20) needs \( S^2 \) multiplications and \( S(S-1) \) additions. Equation (21) needs \( (S-1) \) additions and \( S \) multiplications. As \( \hat{H}_{t,k}(S+1) \) needs to be estimated for \( k \in [0, N-1] \), the total time complexity is \( o(S^2 N) \).

Compared to the complicated signal processing methods, which require autocorrelation sequence estimation, matrix inversion or even singular value decomposition, the complexity of the proposed method is negligible.

B. Data Detection and Decision Feedback Channel Estimation

With the initial estimation of the channel \( \hat{H}_{t,k}(S+1) \), we begin to perform data detection and decision feedback channel estimation. The received data in the DT mode becomes
\[ \mathbf{Y}_d = \mathbf{X}_d^t \cdot \mathbf{H}_d + \mathbf{W}_d \] (22)

where \( \mathbf{H}_d = \text{diag}(H_{d,0}, H_{d,1}, \ldots, H_{d,N-1})^T \) gives the frequency domain channel attenuations and \( \mathbf{W}_d \) is the vector of the uncorrelated complex frequency domain Gaussian random noise. A novel PIC QMMSE/MMSE-PMRC Multi-User Detection/Channel Estimation method is exploited. This method firstly estimates the set of \( h_{(m)}^t (m \in \Theta_0) \) (i.e., the modulated symbols of all the active users) by the combining method based on MMSE criterion. Then the data set is estimated again by MRC method after removing the multiple user interference components from the received signal. Finally the more precise CSI is obtained with decision feedback from the achieved data set. The process may be repeated several times to improve the performance.

First, let \( \hat{\mathbf{H}}_d = \hat{\mathbf{H}}_{t,k}(S+1) \). The output of MMSE combiner for the user \( k \) can be written as
\[ r_{\text{MMSE}(k)} = Q_{\text{MMSE}(k)} \mathbf{Y}_d, \quad 0 \leq k \leq N-1 \] (23)

where \( Q_{\text{MMSE}(k)} = [Q_{\text{MMSE}(k),0}, \ldots, Q_{\text{MMSE}(k),N-1}]^T \) stands for the MMSE equalization gain, which is given by:
\[ Q_{\text{MMSE}}(k) = \left( \sigma^2 l + \frac{M}{N} \right) |\hat{H}_d|^2 \tilde{H}_G(k) \quad 0 \leq k \leq N - 1 \]  

Whereas we only know the number of active users, it is necessary to estimate the active users’ data and the corresponding spread sequence mapping index set \( \Theta_s \) from all the potential \( N \) active users. We then sort all the \( N \) elements of \( \text{abs}(r_{\text{MMSE}}(k)) \) in descending order and get both vector \( r_{\text{SORT}} \) and its corresponding mapping index set \( \Theta_{\text{SORT}} \). The results are divided into three parts shown in Figure 2: \( \Phi_A \) is composed of more reliable data; \( \Phi_B \) includes less reliable data and 0s that needs further steps to handle; \( \Phi_C \) is made of more reliable 0s. Obviously the data elements close to the index \( M \) in Figure 2 have less reliability after sorting. By applying hard decision to \( \Phi_A \) the data vector is

\[ r_{\text{MMSE}, A} = [r_{\text{MMSE}, A(i_1)}, \ldots, r_{\text{MMSE}, A(i_{l_{\text{down}}-1})}]^T \]  

where \( \{ i_1, \ldots, i_{l_{\text{down}}-1} \} = \Theta_A \). Afterward, the contribution of \( I_{\text{down}} \) interfering users is subtracted from the received signal in order to get the corresponding user refined signal with reduced MAI.

\[ \tilde{Y}_{\text{MMSE}} = Y_d - \tilde{H}_d \cdot \sum_{i \in \Theta_A} r_{\text{MMSE}, A(i)} G(i) \]  

The remaining problem is to detect \( M - l_{\text{down}} \) users’ data in \( \Phi_B \) with \( \tilde{Y}_{\text{MMSE}} \). Given that the data in \( \Phi_B \) is less reliable, more powerful GMMSE method can be utilized [20]. However, the complexity of solving a \( N \times N \) linear system for GMMSE should be reduced. First, we define a new vector:

\[ z = [z_1, z_2, \ldots, z_{l_{\text{up}}-l_{\text{down}}}]^T = G^H \tilde{H}_d \tilde{Y}_{\text{MMSE}} \]  

where \( G = [G(k_1), G(k_2), \ldots, G(k_{l_{\text{up}}-l_{\text{down}}})] \); \( \{ k_1, k_2, \ldots, k_{l_{\text{up}}-l_{\text{down}}} \} = \Theta_B \) is the corresponding mapping index set of \( \Phi_B \), and

\[ \tilde{Y}_{\text{MMSE}} = [\tilde{Y}_{\text{MMSE}, 0}, \tilde{Y}_{\text{MMSE}, 1}, \ldots, \tilde{Y}_{\text{MMSE}, N-1}]^T \]. Applying the MMSE criterion to vector \( z \), we get,

\[ r_{\text{MMSE}, B} = Q_{\text{GMMSE}}^H z \quad \text{with} \quad Q_{\text{GMMSE}} = R_{zz}^{-1} R_z \]  

For \( R_{zz} \) and \( R_z \),

\[ R_{zz} = G^H |\tilde{H}_d|^2 G + \sigma^2 I \]  

and

\[ R_z = E(z z^H) = G^H |\tilde{H}_d|^2 G \]

where \( b = [b_{(k_1)}, b_{(k_2)}, \ldots, b_{(k_{l_{\text{up}}-l_{\text{down}}})}] \).

Consequently,

\[ r_{\text{GMMSE}, B} = (G^H |\tilde{H}_d|^2 G + \sigma^2 I)^{-1} G^H |\tilde{H}_d|^2 \tilde{Y}_{\text{MMSE}} \]  

Combining the consequences of equations (25) and (32), the final result and the corresponding index set are:

\[ r_{\text{MMSE}, R} = \begin{bmatrix} r_{\text{MMSE}, A} \\ r_{\text{GMMSE}, B} \end{bmatrix} \]

\[ \Theta_{\text{MMSE}} = \Theta_A \cup \Theta_{B, R} \]  

Clearly a linear \( G \times G \) system needs to be solved instead of the original \( N \times N \) linear system, where \( G = (I_{up} - I_{down} + 1) \). In the system design, the tradeoff between the complexity and the performance varies by selecting different \( G \). Obviously less number of active users makes the detection results more reliable. Hence we can select \( G \) as the fraction of the current active user number.

![Figure 2](image-url)
For most cases $G << N$ and the system's complexity is therefore reduced significantly without loss of the performance. With $\mathbf{r}_{\text{MMSE}_R}$, the system reconstructs the estimated interference of all active users. Afterward, for every active user, the contribution of all the interfering users is subtracted from the received signal, and then MRC is used to get the data detection values. There are many reasons for the usage of the MRC in this stage:

1. The MAI has been cancelled by PIC. Even if there is new active user, the contribution of all the interfering users is almost identical and small, and thus make the total noise effectively white.
2. As mentioned in [21], the CE error variances for all taps are identical and small, and thus make the total noise effectively white.
3. CQS can reduce the MAI of the system effectively with MRC as shown below.

Given the channel estimation inform and $\Theta_\psi$, the MRC coefficients are given as

$$ Q_{\text{MRC}}(i) = [H_{d,0}G_{(k),0},...,H_{d,N-1}G_{(k),N-1}]^T $$

and

$$ r_{\text{MRC}(k)} = Q_{\text{MRC}}(k)Y_d $$

The interference term for user $k$ in equation (36) can be written as

$$ I_k(i) = \sum_{m=0}^{N-1} |H_{d,m}|^2 (\sum_{m=0}^{N-1} h_{d,m}^*G_{(m),m}^* + W_{d,m}H_{d,m}^*)G_{i,m}^* $$

Rewrite it as

$$ I_k(i) = \sum_{m=0}^{N-1} |H_{d,m}|^2 \left( \sum_{m=0}^{N-1} h_{d,m}^*G_{i,m}^* + \sum_{n=0}^{N-1} H_{d,n}W_{d,n}e^{j\frac{2\pi}{N}m}G_{u,n} \right) $$

By applying Plancherel theorem to the MAI term:

$$ I_{k,\text{MAI}} = \sum_{m=0}^{N-1} \sum_{m=0}^{N-1} h_{d,m}^*h_{d,(n-m+k),n}^*b(m) $$

where $h_{d,m}$ is the time domain channel impulse response and it is assumed that $N >> L$, i.e., $h_{d,0} = 0$ when $n > L$. It can be found that $\sum_{n=0}^{N-1} h_{d,n}^*h_{d,(n-m+k),n}^* = 0$ when $(\pm(m-k))_N > L$.

("±" signifies both right and left directions. In other words, when the cyclic shift distance between two users is larger than the maximum delay spread of a multi-path fading channel $L$, there will be no MAI between them at all. Obviously in a full loaded MC-CDMA downlink system, the maximum number of users that can cause interference is reduced from $N-1$ to $2L$ for every user. For a low loaded system, the distances will be all larger than $L$ if we arrange the cyclic shift distances among all the active users in a smart way. It is possible to eliminate MAI completely. In equation (22), $H_d$ and $H$ (Actual CSI) can be considered the same if the difference between them is small. The interference users whose cyclic shift distance to the $k$th user is larger than $L$ will have very small contributions to the MAI. Hence, the detection errors of those users will not affect the result of MRC. It substantially improves the system's performance.

From the results of equations (33) and (34), the contribution of all interfering users is subtracted to achieve a better result.

$$ \hat{Y}_{\text{MRC}(i)} = Y_d - \hat{H}_d \sum_{k \in \Theta_{\text{MMSE}_R}} r_{\text{MMSE}_R}(i)G_{(i),k} $$

$$ \Theta_{\text{MRC}(i)} = \Theta_{\text{MMSE}_R} \cap \Theta_{\text{shift}(k)} $$

where $\Theta_{\text{shift}(k)}$ denotes the set in which every user’s cyclic shift distance to the $k$th user is smaller than or equal to the maximum delay spread of a multi-path fading channel $L$ (Not including $k$ itself).

The MRC is applied to the result of equation (40).

$$ r_{\text{MRC}(k)} = Q_{\text{MRC}}(k)^T\hat{Y}_{\text{MRC}(k)} $$

where $Q_{\text{MRC}}(k)$ represents the MRC equalization gain coefficients.

$$ Q_{\text{MRC}}(k) = \left[ \hat{H}_{d,0}^*,...,\hat{H}_{d,N-1}^*,G_{(k),0},...,G_{(k),N-1}^* \right] $$

With the result of equation (42), we get

$$ \tilde{X}_d = \sum_{m \in \Theta_{\text{MMSE}_R}} \text{HardDecision}(r_{\text{MRC}(k)})G_{(m)} $$

By following the same procedure shown in the PT mode, the decision feedback estimated CSI is obtained as $\hat{H}_{d,r}$. The final result can be received by assigning $\hat{H}_{d,r}$ to $\hat{H}_d$ and redoing the whole process from equation (23) until the estimated CSI is converged (or the maximum iteration is achieved). We store the current CSI estimation $\hat{H}_d(u) = \hat{H}_{d,r}$, where $u$ is the current symbol index. The $\hat{H}_d(u)$ vector is put into a first in first out (FIFO) queue and will be used as a previous CSI observation in the next channel prediction process. Finally, the data detection value of current mobile user $l$ is:

$$ b_{(l)} = \text{HardDecision}(r_{\text{MRC}(k)}) $$

Due to the property of CQS, even in a full load system only 2L users are needed to be cancelled in the interference cancellation part, which the number is much less than original $N-1$. This partial cancellation also improves the system’s performance because the errors involved from the process of cancellation have been decreased greatly.
3. Simulation and Analysis

The BER performance of the proposed system is evaluated by the use of software simulation. The main parameters used in the simulation are summarized in Table 1. 3GPP deployment channel models TR 25.943 are exploited in this paper [22]. A typical urban channel model and a rural area channel model are tested. The maximum Doppler Frequency is set to 111 Hz, which leads to a high speed mobile communication system. During the simulation, 7 OFDM symbols of pilots are transmitted in the PT mode period. After 96 DT OFDM symbols’ transmission, the system enters another PT mode period. Figure 3 shows the BER simulation results under 3GPP TR 25.943 typical urban channel model with $E_b/N_0=0\text{dB}$. The solid curve is the proposed PIC-QMMSE/MMSE-PMRC method. The solid curve with circles results from the proposed receiver with the complete cancellation strategy, where WMRC denotes the Whole MRC. The solid curve with triangles represents PIC-MMSE-PMRC. Besides all above three receivers with CQS, the result of traditional PIC-MMSE-WMRC (Walsh Codes) receiver is marked as the solid curve with squares. The simulation results under 3GPP TR 25.943 typical rural channel model are given in Figure 4 in the same way.

In Figures 3 and 4, both methods with QMMSE/MMSE outperform over the other two methods using pure MMSE. Because the precision of initial detection is very important in the interference cancellation based MUD, it is necessary to refine unreliable data with the proposed QMMSE/MMSE method and the result will bring a drastic improvement with a moderate increase in its complexity. We also notice that the PIC-MMSE-PMRC (CQS) outperforms over the PIC-MMSE-WMRC (Walsh Codes). This is due to the unique MAI suppression advantage of CQS in the multi-user environment shown in [12]. Also, CQS can effectively reduce the PAPR because it provides the constant envelope property.

Since PAPR and MAI minimization are two very important issues [23], we believe that the CQS is a good choice for MC-CDMA systems. After comparing the performances of proposed PIC-QMMSE/MMSE-PMRC scheme and the PIC-QMMSE/MMSE-WMRC, we find that our proposed method takes minor advantage on a low loaded system that includes a few active users. However, the advantage becomes more explicit when the number of active users increases. In a low loaded system, the system is prone to getting more precise channel estimation information and user detection values. There are no significant differences if we cancel part of them or all of them. However when the number of active users is increased, the imprecise channel estimation and erroneous user detection become more and more serious and more errors will be involved in the process of the data cancellation. Hence canceling part of them not only decreases the complexity but also mitigates the errors brought by the interference cancellation process. In full loaded case, the advantage of proposed method is not that obvious since there are considerable $2L$ active users forming the effective interference.

The channel tracking minimum square errors (MSE) results for a full-loaded MC-CDMA system are shown in Figures 5 and 6 that $E_b/N_0$ are set to 5dB and 20 dB, respectively. In Figure 5, the proposed method has the smallest channel MSE while all methods are losing their channel track gradually as time goes by. In Figure 6, the performance of our proposed method is still the best one. In all the cases of both Figures, the PIC-MMSE-WMRC (Walsh codes) has the worst performance, which shows that the CQS plays a key role to help the system improve the channel tracking ability. It also should be noticed that PIC-MMSE-PMRC outperforms PIC-QMMSE/MMSE-WMRC when $E_b/N_0$ is relatively high (20dB), and the reverse happens when $E_b/N_0$ is relatively low (5dB). This can be explained as follows: When noise impact is small, the difference between QMMSE and MMSE becomes less important. While compared with PMRC, the WMRC for CQS unnecessarily cancels those active users whose cyclic shift distance to the current user is larger than the maximum delay spread of a multi-path fading channel $L$. This increases the complexity and causes the error propagation due to the erroneous symbol decision feeding back, which leads to the found result. On the other hand, when noise impact is relatively large, the difference between MMSE and GMMSE becomes dominant. Therefore PIC-QMMSE/ MMSE-WMRC is better than PIC-MMSE-PMRC under this circumstance. In a word, the PMRC on PIC and QMMSE/MMSE improves the performance from the different aspects, which promises the
proposed scheme outperforms others in different conditions.

Besides the outstanding performance, the proposed system complexity is relatively low as well. As we mentioned early, Compared to the complicated signal processing methods, which require autocorrelation sequence estimation, matrix inversion or even singular value decomposition, the complexity $o(S^2N)$ of the proposed channel tracking method is negligible. $o(G^2)$ for proposed MMSE/GMMSE method is also a big improvement to $o(N^2)$ of the QMMSE scheme. In PMRC-PIC part, through the use of CQS, only $2L$ number of users needs to be cancelled out from all users in the worst case. This is a great improvement compared to the system applying Walsh Codes, which need to cancel $N-1$ users in the worst case.

4. Conclusion

In this work we present a novel receiver structure with joint PIC detection and channel predicting and tracking for a downlink MC-CDMA system. The noise variance and channel information are not necessarily known in advance. The Combination of MMSE and GMMSE is adopted and good results are obtained with significantly reduced effort compared to pure GMMSE scheme. With the use of Partial MRC PIC scheme based on CQS, we improve the performance and reduce the complexity simultaneously. The simulation results and analysis show our proposed system has good BER performance and channel tracking ability in different channels and system loading conditions.
References


