Programmable Multiuser Synchronization for OFDM-CDMA

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Abstract— *A more effective synchronization is required for multiuser detection [10] because of its high sensitivity to estimation errors of timings, carrier phases, and amplitudes. From the multiuser synchronization approach proposed in [11], we develop a linear-complexity programmable multiuser synchronization structure for OFDM-CDMA in a multiray fading channel. Based on LMMSE and BLUE, we develop joint estimation of timings, carrier phases, and amplitudes. The structure can be programmed to various OFDM-CDMAs by adjusting system parameters and its performance is also verified by simulations. An algorithm is further proposed to avoid irrelevant calculations of FFT. The proposed structure is valuable and desirable for its programmability and near-far resistance.*

I. Introduction

In high rate CDMA communications, signals are subject to frequency selective fading and therefore severe multiple access interference (MAI) unless a more complicated equalizer or equivalence is adopted. Three schemes combing orthogonal frequency division multiplexing (OFDM) [1], well known as multicarrier CDMA (MC-CDMA) [3], multicarrier direct sequence CDMA (MC-DS-CDMA) [4], and multitone CDMA (MT-CDMA) [5] were proposed to solve this problem. Thus a programmable OFDM-CDMA transceiver architecture [7] was developed based on the unified framework, OFCDMA [8].

A programmable multiuser detection structure [9] was then proposed to enhance the performance of the programmable OFDM-CDMA receiver, which assumes users' timings, amplitudes, carrier phases available. It was pointed [15] that the performance of multiuser detectors is highly sensitive to timing jitter. Therefore, an effective synchronization is desired for general OFDM-CDMA.

Synchronization in near-far environment is a challenge due to severe MAI. Multiuser synchronizations for CDMA [11][12][13][14] have been proposed to solve this issue while a general multiuser synchronization scheme for OFDM-CDMA is still desired. In this paper we extend a linear-complexity programmable multiuser synchronization structure for OFDM-CDMA based on Chang's framework [11].

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The optimum synchronizer in a multiray Rayleigh fading channel is first derived. Then, a programmable structure based on linear minimum mean square error (LMMSE) and best linear unbiased estimator (BLUE), for different OFDM-CDMA systems has been illustrated. An efficient algorithm is further proposed to reduce computations of fast Fourier transform (FFT). The performance and implementation issues are then discussed.

II. Optimum multiuser synchronization

Consider the uplink case for a general OFDM-CDMA system. In what follows, signals are represented by their lowpass equivalent envelopes for ease of analysis. The the k^{th} user's transmitted signal is

$$s_k(t) = \sqrt{2a_k/JM}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{p=-P}^{P} b_{kj}(t)c_{km}(t-pT)e^{\imath w_{jm}t},$$

where a_k is the transmission power, $b_{kj}(t)$ is the information-bearing signal on the $(jm)^{\text{th}}$ subcarrier $e^{\imath w_{jm}t}$; $c_{km}(t)$ is the T-durationed signature waveform for the $(jm)^{\text{th}}$ subcarrier. It is assumed that there are $2P+1$ transmitted symbols on each subchannel for each user and the number of subcarriers is JM. The j and m are called the index of independent and dependent subcarriers respectively because $e^{\imath w_{jm}t}$ carries independent information for different j while identical information for all m.

It is assumed that the k^{th} user's transmission signal on the $(jm)^{\text{th}}$ subchannel is subject to a L-ray Rayleigh fading channel with channel impulse response $h_{kjm}(t) = \sum_{l=1}^{L} g_{kjml}\delta(t-t_{kl})$. Where the channel coefficients g_{kjml} are assumed zero-mean complex Gaussian random variables, and $t_{kl} \in [(l-1)T_c, lT_c]$ is the delay corresponding to the l^{th} ray of the k^{th} user's signal. Let $b_{kj}[p]$ be the p^{th} symbol of the $b_{kj}(t)$ and the number of users be K, the received signal at the base station is

$$\begin{aligned} v(t) &= \sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{l=1}^{L}\sum_{p=-P}^{P} \beta_{kjml}b_{kj}[p] \\ &\quad c_{km}(t-pT-\tau_k-t_{kl})e^{\imath w_{jm}t} + \eta(t), \end{aligned}$$

where $\beta_{kjml} \equiv \sqrt{2a_k/JM}g_{kjml}$, and τ_k is the timing of user k. Without loss of generality, we consider the phase shift $-w_{jm}(\tau_k + t_{kl})$ into g_{kjml}; $\eta(t)$ is a zero-mean complex AWGN process with variance σ^2.

For notational convenience, we introduce the block matrix construction method mentioned in [9], which states that a variable with less subscripts represents a block vector (a bold-faced lowercase letter) or a block matrix (a bold-faced capital letter) constructed from itself with more subscripts by sequencing the additional ones. For example, $\boldsymbol{x}_{km}$ is a larger dimensional vector constructed from a smaller dimensional vector $\boldsymbol{x}_{kjml}$ by $\boldsymbol{x}_{km} \equiv [\boldsymbol{x}_{k1m1}^T, ..., \boldsymbol{x}_{kJm1}^T, \boldsymbol{x}_{k1m2}^T, ..., \boldsymbol{x}_{kJm2}^T, ..., \boldsymbol{x}_{kJmL}^T]^T$. Among the subscripts, a lowercase letter (e.g. k and k') represents the index of the elements while the capital letter (e.g. K) represents the total number of the corresponding elements.

It is assumed that the training interval T_t is short enough ($T_t << 1/f_D$, where f_D is the Doppler frequency) such that timings, phases, and amplitudes remain constant during training. Based on maximum likelihood criterion, the optimum estimator for the synchronization parameters $\boldsymbol{\beta}$, and $\boldsymbol{\tau}$ can be obtained by

$$\arg\max_{\widehat{\boldsymbol{\beta}},\widehat{\boldsymbol{\tau}}} \Pr(v(t)|\boldsymbol{\beta}, \boldsymbol{\tau}, \boldsymbol{d}[p]). \tag{1}$$

Unfortunately, it is impossible to solve this problem directly without further assumptions.

Unlike multiuser detection, gradient-based searching algorithms may fail to find the global maximum of $\Pr(v(t)|\boldsymbol{\beta}, \boldsymbol{\tau}, \boldsymbol{d}[p])$ because it is not a convex function. Therefore, the conventional two-stage timing recovery policy is adopted: acquisition and tracking. The former is to coarsely estimate the possible timing interval such that gradient-based searching algorithms are applicable to the latter for a finer timing. In this paper, we concentrate on timing acquisition.

Let $\zeta_{kjmlu} \equiv \beta_{kjml}\delta_{\psi_u,\tau_k}$, where $\delta_{x,y}$ is the Kronecker delta function. Under the discrete timing assumption (DTA) [11], that is τ_k belongs to a finite set $\{\psi_u : u = 1, 2, ...U\}$, and furthermore $t_{kl} = (l-1)T_c$, (1) becomes $\arg\max_{\widehat{\boldsymbol{\beta}},\widehat{\boldsymbol{\tau}}} \Omega(\boldsymbol{\zeta})$, where

$$\begin{aligned}\Omega(\boldsymbol{\zeta}) &= 2Re\left\{\sum_{p=-P}^{P} \boldsymbol{\zeta}^H \boldsymbol{D}^H[p]\boldsymbol{v}[p]\right\} - \\ &\sum_{p=-P}^{P}\sum_{p'=-P}^{P} \boldsymbol{\zeta}^H \boldsymbol{D}^H[p]\boldsymbol{R}[p-p']\boldsymbol{D}[p']\boldsymbol{\zeta}. \end{aligned} \tag{2}$$

$(.)^H$ denotes the conjugate transpose operation of a matrix, and $Re(.)$ denotes the real part of a complex number. The $KJMLU \times 1$ observation vector $\boldsymbol{v}[p\ ]$ is constructed from

$$v_{kjmlu}[p] = \int_{-\infty}^{\infty} v(t)c_{km}^*(t - pT - \psi_u - t_{kl})e^{-\imath w_{jm} t}dt, \tag{3}$$

where $(.)^*$ denotes the complex conjugate. Summarizing those indexes: k is used for users, j for independent subcarriers, m for dependent subcarriers, l for rays, and u for possible timing instants. A prime notation is also used if necessary, such as $k'\ j'\ m'\ l'\ u'$. The $KJMLU \times KJMLU$ correlation matrix $\boldsymbol{R}[p-p']$ is constructed from

$$\begin{aligned}&R_{kjmlu,k'j'm'l'u'}[p-p'] = \int_{-\infty}^{\infty} c_{km}^*(t - pT - \psi_u - t_{kl}) \\ &c_{k'm'}(t - p'T - \psi_{u'} - t_{k'l'})e^{-\imath(w_{jm} - w_{j'm'})t}dt.\end{aligned}$$

The reference matrix $\boldsymbol{D}[p] = diag(\ \boldsymbol{D}'[p], \boldsymbol{D}'[p], ..., \boldsymbol{D}'[p])$ is a $KJMLU \times KJMLU$ diagonal matrix in which $\boldsymbol{D}'[p]$ is a $KJ \times KJ$ diagonal matrix constructed from the training sequences $d_{kj}[p]$.

Letting $\boldsymbol{\zeta} = \boldsymbol{B\delta}$ (by $\zeta_{kjmlu} \equiv \beta_{kjml}\delta_{\psi_u,\tau_k}$) in (2), we observe that if the diagonal amplitude matrix $\boldsymbol{B}$ is known in advance, the maximum likelihood sequence detection (MLSD) approach, which searches for all possible $\boldsymbol{\delta}$ such that (2) is maximized, is applicable. On the contrary, if the timing $\boldsymbol{\delta}$ is known in advance, the amplitude $\boldsymbol{B}$ can be easily estimated. Hence, it is possible to develop an algorithm which recursively estimates $\boldsymbol{\delta}$ and $\boldsymbol{B}$. Furthermore, the MLSD approach may still be applicable if the amplitudes are assumed discrete-valued such that the number of possible values of $\boldsymbol{\zeta}$ is finite. After $\boldsymbol{\zeta}$ is estimated, say $\widehat{\boldsymbol{\zeta}}$, we can get $\widehat{\tau}$ and $\widehat{\beta}$ by

$$\widehat{u}_k = \arg\max_u |\zeta_{ku}|\,, \ \widehat{\tau}_k = \psi_{\widehat{u}_k}, \ \widehat{\beta}_{kjml} = \zeta_{kjml\widehat{u}_k}. \tag{4}$$

III. Programmable multiuser synchronization

Under the discrete timing assumption, the performance function $\Omega(\boldsymbol{\zeta})$ becomes a quadratic form. Similar to those techniques used in multiuser detection, we are going to derive a linear-complexity programmable multiuser synchronization structure. All that needed in multiuser synchronization can be acquired from the received signal $v(t)$ via the programmable OFDM-CDMA receiver proposed in [7]. Hence the derived synchronizer is undoubtedly programmable. We then demonstrate how the synchronizer is programed to different OFDM-CDMA systems.

From (3), $\boldsymbol{v}[p]$ may be expressed as

$$\boldsymbol{v}[p] = \sum_{p'=-P}^{P} \boldsymbol{R}[p-p']\boldsymbol{D}[p']\boldsymbol{\zeta} + \boldsymbol{\eta}[p]. \tag{5}$$

The idea is based on linearly combining the sufficient statistics $v_{kjmlu}[p]$. Let $\boldsymbol{R}$ and $\boldsymbol{D}$ be $KJMLU(2P+1) \times KJMLU(2P+1)$ matrices with $\boldsymbol{R}_{p,p'} = \boldsymbol{R}[p-p']$, $\boldsymbol{D}_{p,p'} = \delta_{p,p'}\boldsymbol{D}[p]$; $\boldsymbol{\eta}$ be a $KJMLU(2P+1) \times 1$ vector with $\boldsymbol{\eta}_p = \boldsymbol{\eta}[p]$; $\boldsymbol{J} = [\boldsymbol{I}, \boldsymbol{I}, ...\boldsymbol{I}]^T$ be a $KJMLU(2P+1) \times KJMLU$ matrix constructed from the $KJMLU \times KJMLU$ identity matrix $\boldsymbol{I}$; It is obvious that

$E[\boldsymbol{\eta}[p]\boldsymbol{\eta}[p']^H] = \sigma^2 \, \boldsymbol{R}[p-p']$ and hence $E[\tilde{\boldsymbol{\eta}}\tilde{\boldsymbol{\eta}}^H] = \sigma^2 \boldsymbol{R}$. Then (5) can be expressed as

$$\boldsymbol{v} = \boldsymbol{RDJ\zeta} + \boldsymbol{\eta}. \tag{6}$$

For single user approach, the optimum estimator based on maximizing signal to noise ratio (SNR) is

$$\widehat{\boldsymbol{\zeta}} = \boldsymbol{J}^H \, \boldsymbol{D}^H \boldsymbol{v}, \tag{7}$$

which is just the maximum ratio combing (MRC) of $\boldsymbol{v}$.

For multiuser approaches, let $\boldsymbol{A}$ be a linear operator such that $\widehat{\boldsymbol{\zeta}} = \boldsymbol{Av}$. The LMMSE estimator is

$$\boldsymbol{A}_{MS} = (\boldsymbol{J}^H\boldsymbol{D}^H\boldsymbol{RDJ} + \sigma^2\boldsymbol{C}_{\zeta}^{-1})^{-1}\boldsymbol{J}^H\boldsymbol{D}^H, \tag{8}$$

where $\boldsymbol{C}_{\zeta} = E[\boldsymbol{\zeta\zeta}^H]$. And the BLUE is

$$\boldsymbol{A}_{BL} = (\boldsymbol{J}^H\boldsymbol{D}^H\boldsymbol{RDJ})^{-1}\boldsymbol{J}^H\boldsymbol{D}^H. \tag{9}$$

Observe that $\boldsymbol{A}_{MS}$ and $\boldsymbol{A}_{BL}$ require $\boldsymbol{v}$, $\boldsymbol{R}$, $\boldsymbol{C}_{\zeta}$, and $\boldsymbol{D}$. $\boldsymbol{R}$ and $\boldsymbol{D}$ can be stored in the database. $\boldsymbol{C}_{\zeta}$ can be easily estimated or assigned empirically at the first moment and then tracked adaptively. Therefore, if the process for getting $\boldsymbol{v}$ is programmable, then the two estimation approaches for $\boldsymbol{\zeta}$ are also programmable. It is also true for the multiuser synchronization structure which further processes $\hat{\boldsymbol{\zeta}}$ by (4).

In fact, $\boldsymbol{v}$ can be produced from $v(t)$ via the programmable OFDM-CDMA with a sequence of shifted $v(t)$, that is $v(t+\psi_v+t_n)$. The i^{th} user's RAKE receiver architecture for the programmable OFDM-CDMA is depicted in Figure 1 [7] where the n^{th} finger is shown in Figure 2 [7]. The synchronized signal is sampled at rate $f_s = G/T_c$. After each S/P conversion the GH/N samples are shift zero-padded to GH ones, by which we mean that the GH/N samples are zero-padded to GH samples and end-roundly shifted by nGH/N samples for $n = 0, 1, ...N-1$, where $G = \lceil (MJ-1)\frac{T_c}{T_o} + 1 \rceil$ and $H = \frac{T_o}{T_c}$. Next, a GH-point FFT is performed and then only the first MJ samples are retained after windowing. At last, the MJ parallel branches are block-multiplexed to M tapped-delay-lines with weightings c_{is}^n for despreading. Note that if the $v(t)$ is replaced by $v(t-\psi_v)$, the final outputs v_{irsn} correspond to v_{kjmlu} defined in (3). The relation between the programmable multiuser synchronizer, detector and receiver is shown in Figure 3. The structure in Figure 3 is computation-consuming because $\boldsymbol{v}_{u+a}$ are calculated independently for $a = 0, 1, ...U-1$ even though they are correlated. A more efficient structure is proposed and the details are shown in Figure 4 with additional blocks "S/P", "interpolation", and "Mux". The block "Update ALG" standing for "update algorithm" is discussed in the next section. Because the fundamental structure of the synchronizer is the same as that of the programmable OFDM-CDMA receiver, the proposed linear synchronization is still programmable.

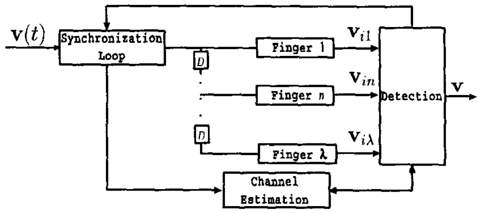

Fig. 1. The i^{th} user's OFDM-CDMA RAKE receiver architecture

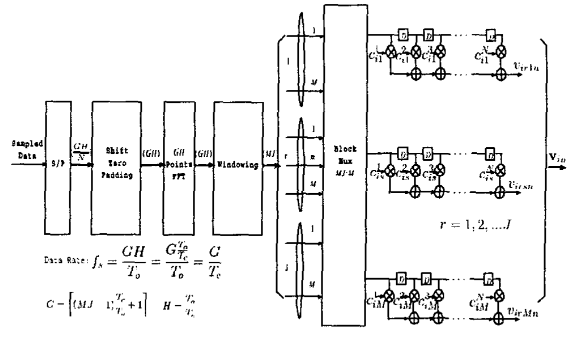

Fig. 2. The n^{th} finger of the OFDM-CDMA RAKE receiver

We now demonstrate how the multiuser synchronization structure is programmed to the MC-CDMA, MC-DS-CDMA, and MT-CDMA respectively. Parameter settings are summarized inside Figure 3.

A. Programming to MC-CDMA

Assuming that $U = U_oGH$, the inverse of adjacent subcarriers separation is set to $T_o = T_c = T$, and the data sampling rate is $f_s = \frac{U_oMJ}{T_o} = \frac{U_oM}{T'}$. The two blocks "shift zero padding" and "windowing" are not needed for $H = 1$ and $GH = MJ$. The tapped-delay-lines regress to be one-tap ($N = 1$), that is $c_{km}^1 = c_k^m$ for $m = 1, 2, ...M$. The correlation matrix $\boldsymbol{R}^{MC}$ is chosen with

$$R^{MC}_{kjmlu,k'j'm'l'u'}[p-p'] = (c_k^m)^* c_{k'}^{m'} \int_{-\infty}^{\infty} \Pi(t-pT-\psi_u - t_{kl})\Pi(t-p'T-\psi_{u'}-t_{k'l'})e^{-\imath\frac{2\pi}{T}((j-r)+J(m-s))t}dt,$$

where $\Pi(t) \equiv 1$ for $t \in [0, T]$ and $\Pi(t) \equiv 0$ otherwise.

B. Programming to MC-DS-CDMA

We set $T_o = T_c = \frac{T}{N_{MD}}$ and $f_s = \frac{U_oMJ}{T_c} = \frac{U_oN_{MD}}{T'}$. The "shift zero padding" and "windowing" are not needed because $H = 1$ and $GH = MJ$. The weighting coefficients are identical for all tapped-delay-lines, that is $c_{km}^n = c_k^n$, $n = 1, 2, ...N_{MD}$. The correlation matrix $\boldsymbol{R}^{MD}$ is chosen with

$$R^{MD}_{kjmlu,k'j'm'l'u'}[p-p'] = \int_{-\infty}^{\infty} c^*_{km}(t-pT-\psi_u-t_{kl})$$
$$c_{k'm'}(t-p'T-\psi_{u'}-t_{k'l'})e^{-\imath\frac{2\pi N_{MD}}{T}((j-r)+J(m-s))t}dt.$$

C. Programming to MT-CDMA

For the MT-CDMA in which $M=1$, we let $T_o=T$ and $f_s=\frac{U_oGH}{T}=\frac{U_oGH}{JT'}$, and $c^n_{k1}=c^n_k$ for $n=1,2,...N_{MT}$. The correlation matrix $\boldsymbol{R}^{MT}$ is chosen with

$$R^{MT}_{kjlu,k'j'l'u'}[p-p'] = \int_{-\infty}^{\infty} c^*_k(t-pT-\psi_u-t_{kl})$$
$$c_{k'}(t-p'T-\psi_{u'}-t_{k'l'})e^{-\imath(\frac{2\pi}{T}(j-r)t}dt.$$

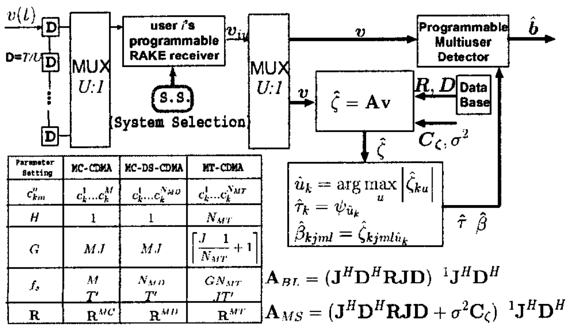

Fig. 3. The programmable multiuser synchronization structure for OFDM-CDMA

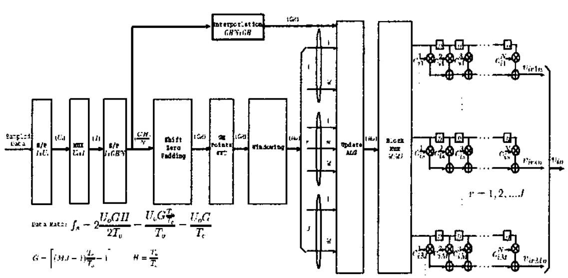

Fig. 4. An efficient synchronization structure modified from the programmable OFDM-CDMA receiver

IV. The update algorithm

Since $\boldsymbol{v}_u$ and $\boldsymbol{v}_{u+a}$ are correlated for $a=1,2,...U-1$, some repeated processings are avoidable. Given a sequence $\{x_0,x_1,...,x_{N-1},x_N,...,x_{2N-1}\}$, let us consider getting $\boldsymbol{y}^m$ in terms of $\boldsymbol{y}^0$ and other parameters, where $\boldsymbol{y}^m$ is an N-vector representing the N-point discrete Fourier transform (DFT) of $\boldsymbol{x}^m=[x_m,x_{m+1},...,x_{m+N-1}]^T$.

The N-point DFT of $\boldsymbol{x}^m$ is $y^m_k=\sum_{n=0}^{N-1}x_{n+m}W^{nk}$, where $W=e^{-\imath\frac{2\pi}{N}}$. It is very straightfoward that

$$\begin{aligned} y^m_k &= \sum_{n=0}^{N-1}x_{n+m}W^{nk} = \sum_{n=m}^{m+N-1}x_nW^{(n-m)k} \\ &= W^{-mk}(y^0_k+\sum_{n=0}^{m-1}(x_{n+N}-x_n)W^{nk}). \quad (10)\end{aligned}$$

Therefore, we can get $\boldsymbol{y}^m$ in terms of $\boldsymbol{y}^0$ and $\{x_n,x_{n+N}: n=0,1,...m-1\}$ by (10). We see that given the old data $\{x_0,x_1,...,x_{m-1}\}$ and the updating data $\{x_N,x_{N+1},...,x_{N+m-1}\}$, $\boldsymbol{y}^m$ can be obtained in terms of $\boldsymbol{y}^0$ without directly computing the DFT of $\boldsymbol{x}^m$.

Assuming the number of the discrete timing set is $U=U_oGH$. Only the $m=1$ case should be considered in (10), that is for $k=0,1,...GH-1$, $y^{i+1}_k=W^{-k}(y^i_k+x_{n+N}-x_n)$. The structure for the update algorithm is shown in Figure 5. When GH cannot divide U or U cannot divide GH, additional interpolations are required. Therefore, for practical applications, it is more efficient to design GH and U such that either of them can divide the other.

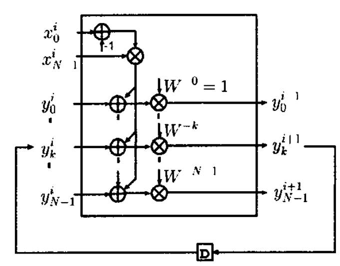

Fig. 5. The structure of the update algorithm

V. Performance Evaluation and implementation issues

We have shown a programmable multiuser synchronization structure for the OFDM-CDMA. The programmability is still preserved because all that needed for estimation can be obtained using the original receiver structure. It is shown in [11] that in CDMA, the modified mean square of error for timings and complex amplitudes tends to zero as SNR tends to infinity. We then want to figure out whether this property is true in OFDM-CDMA or not.

Let us assume the number of rays $L=1$ for illustration. Observing (2), $\boldsymbol{R}$ can be regarded as a new cross-correlation matrix for imaginary users $\bar{k}=1,2,...,KJM$ with signature waveforms being $c_{\bar{k}=kjm}(t)=c_k(t)e^{\imath w_{jm}t}$. Therefore, the K-user OFDM-CDMA system can be considered as a special case of a KJM-user CDMA system with new signature waveforms generated from the original signature waveforms and the subcarriers. Therefore, all characteristics for multiuser synchronization in CDMA are inherited by OFDM-CDMA. This implies that the proposed programmable multiuser synchronization structure for OFDM-CDMA is also near-far resistant.

We now show the simulation results when the programmable synchronizer is set to the MC-DS-CDMA system. A 4-user, 1-independent subcarrier, 4-dependent subcarrier case is considered ($(K, J, M) = (4, 1, 4)$) with the length of training sequences being $2P + 1 = 1$. It is assumed that the number of subcarriers $JM = 4$ is designed such that the signal undergoes flat fading ($L = 1$) on each subchannel and β_{kjml} are identically and independently distributed with variance $1/(JM) = 1/4$. The discrete timings are $\psi_u = u/T' = u/(MT) = u/(4T)$, for $u = 0, ..., 3$ and are uniformly distributed. Gold codes of length 15 are used and the BLUE, LMMSE and MRC approaches are compared. Figure 6 shows the acquisition error rate and mean square error of the complex amplitude in different SNRs, which verifies that the BLUE and LMMSE are near-far resistant in a frequency selective fading channel. When SNR is high, the performance of BLUE is close to the better LMMSE. Quite different

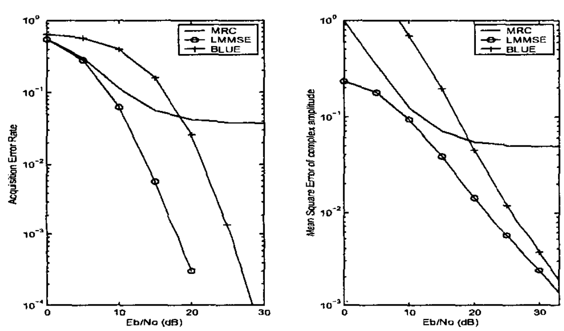

Fig. 6. The probability of acquisition and mean square error of the complex amplitude for multiuser LMMSE, BLUE and single user MRC approaches.

from multiuser detection, the linear operator $\boldsymbol{A}_{BL}$ is deterministic in multiuser synchronization. The complexity is of $o(N^2)$ where N is the size of $\boldsymbol{A}_{BL}$. Therefore, the BLUE is preferred for its low complexity compared to LMMSE. On the other hand, for the LMMSE estimator, we can store a collection of data about $\boldsymbol{A}_{MS}(\boldsymbol{C}_\zeta, \sigma^2)$ in the hardware under some empirical estimates of $\boldsymbol{C}_\zeta$ and σ^2. Once the $\boldsymbol{C}_\zeta$ and σ^2 are determined, $\boldsymbol{A}_{MS}(\boldsymbol{C}_\zeta, \sigma^2)$ can be chosen from the database.

Note that in our analysis the value of the reference matrix $\boldsymbol{D}$ (or reference sequences $d_{kj}[p]$) is not specifically assigned. It may be possible to design $\boldsymbol{D}$ such that $\boldsymbol{J}^H \boldsymbol{D}^H \boldsymbol{R} \boldsymbol{D} \boldsymbol{J}$ is diagonal. If this is the case, then from (2), the single user approach in (7) becomes the optimum solution. Therefore, it is very important in designing the training sequences and this subject leaves much more for further study.

VI. Conclusions

A linear-complexity programmable multiuser synchronization structure for OFDM-CDMA is developed to enhance system performance. In addition to the BLUE and LMMSE estimators are considered for estimating $\boldsymbol{\zeta}$, other types of estimators can be derived accordingly. The update algorithm is further proposed to avoid irrelevant computations of FFT. The synchronization structure succeeds to the features in CDMA because we may think of the OFDM-CDMA as a special case of CDMA with more imaginary users and the performance is further verified by simulation. The low-complexity BLUE performs well at high SNR. The LMMSE outperforms BLUE and MRC, and if the database-lookup approach is used its complexity is as low as that of BLUE. It is also possible to design the training matrix $\boldsymbol{D}$ so that $\boldsymbol{J}^H \boldsymbol{D}^H \boldsymbol{R} \boldsymbol{D} \boldsymbol{J}$ is diagonal, and then a large number of computations can be reduced.

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