Multi-user Joint Tx/iterative Rx MMSE-FDE And Successive MUI Cancellation For Uplink DS-CDMA

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***Abstract*—Uplink multi-user direct sequence-code division multi-access (DS-CDMA) suffers from strong multi-user interference (MUI) and self inter-chip interference (ICI) caused by severe frequency-selective fading. In this paper, we propose a joint Tx/iterative Rx frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion and successive MUI cancellation (MUIC) for DS-CDMA uplink. In the proposed scheme, each user applies one-tap Tx FDE before transmitting signal. At the base station, joint one-tap Rx FDE and successive MUIC is iteratively performed. The FDE weights of users and base station are jointly optimized based on the MMSE criterion in order to reduce MUI and ICI while exploiting channel frequency-selectivity. Computer simulation results show that the proposed scheme provides much improved bit error rate (BER) performance than the conventional iterative Rx MMSE-FDE with successive MUIC.**

Keywords-component; Frequency-domain equalization, DS-CDMA, Uplink, MUI cancellation

I. INTRODUCTION

Direct-sequence code division multi-access (DS-CDMA) is a promising multi-access technology for wideband cellular networks [1]. However, as the chip rate increases, strong inter-chip interference (ICI) is produced due to severe frequency-selective fading channel. One-tap frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion has been gaining much attention for downlink DS-CDMA [2,3] since it is able to achieve good bit error rate (BER) performance by suppressing the ICI while exploiting channel frequency-selectivity. However, the residual ICI after MMSE-FDE limits the achievable BER performance improvement. In order to further reduce the residual ICI after MMSE-FDE, iterative MMSE-FDE and ICI cancellation (ICIC) was proposed [4,5]. In this scheme, at first, a series of one-tap Rx FDE and despreading is carried out. The residual ICI replica is computed using the log-likelihood ratio (LLR) of the decision variables. Then, a series of Rx FDE, ICIC, and despreading is repeated sufficient number of times. In each iteration stage, Rx FDE weight is updated based on the MMSE criterion by taking into account the residual ICI power after the cancellation. It was shown that the iterative Rx MMSE-FDE and ICIC provides much better performance than the simple Rx MMSE-FDE. Recently, in [6], we proposed a joint Tx/iterative Rx MMSE-FDE and ICIC suitable for single-user multicode DS-CDMA (i.e., downlink), in which one-tap Tx FDE at the transmitter is performed before transmitting signal, while the receiver employs the iterative Rx FDE and ICIC. A set of Tx and Rx FDE weights is jointly optimized based on the MMSE criterion. In DS-CDMA uplink, however, different users' signals go through different frequency-selective fading channels and therefore, strong multi-user interference (MUI) is produced [7].

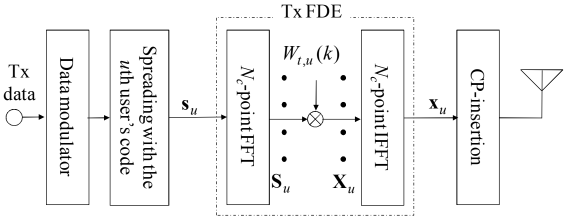
So far, iterative MMSE-FDE and successive MUI cancellation (MUIC) was proposed for DS-CDMA uplink in [8-11]. In this scheme, not only ICI but also MUI are cancelled in an iterative manner at a base station. In this paper, we introduce the successive MUIC to extend the scheme in [6] for DS-CDMA uplink and propose a joint Tx/iterative Rx MMSE-FDE and successive MUIC. Each user performs one-tap Tx FDE before transmitting the signal. After receiving the signals, iterative Rx FDE and successive MUIC is carried out at the base station. We jointly optimize the FDE weights of users and base station based on the MMSE criterion, where the residual ICI and MUI are taking into account for optimization. We show by computer simulation that the proposed scheme much increases the number of multi-access users in a severe frequency-selective fading channel.

The rest of this paper is organized as follows. Section II describes the signal representation of joint Tx/iterative Rx MMSE-FDE and successive MUIC. In Sect. III, a set of MMSE-FDE weights are derived. Section IV shows the computer simulation results. Section V concludes this paper.

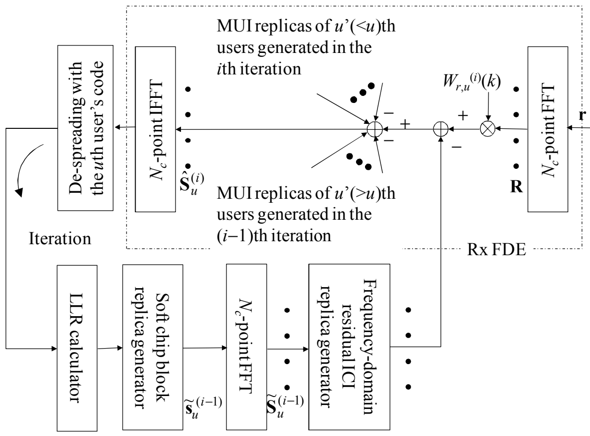
II. SIGNAL REPRESENTATION

In this paper, chip-spaced discrete-time baseband signal representation is used. We assume that the users' transmit timings are asyncronous but they are kept within the cyclic prefix (CP); the sum of maximum transmit timing offset among users and channel maximum delay time is less than the CP length. The fast Fourier transform (FFT) (or inverse FFT (IFFT)) block size and CP length are denoted by N_c and N_g, respectively. Without loss of generality, we consider the transmission of one block in this section. The number of users is denoted by U, each communicates to the base station using user-specific spreading code with the spreading factor SF.

Figure 1 illustrates a transceiver design of the proposed scheme. It should be noted that the successive MUIC that will be described later can be easily replaced by a parallel MUIC.



(a) Transmitter of the uth user, u=0~(U–1)



(b) Receiver

Fig.1 Transceiver design.

A. Transmit signal

At the transmitter of the uth user, u=0~(U–1), a data-modulated symbol block $\{d_u(m);\ m=0\sim N_c/SF-1\}$ is spread by a user-specific spreading code, $c_u(n)$. The resultant chip block $\{s_u(n);\ n=0\sim N_c-1\}$ of the uth user is written as

$$s_u(n)=\sqrt{2E_{u,c}/T_c}\,d_u(\lfloor n/SF\rfloor)c_u(n), \tag{1}$$

where $E_{u,c}$ and T_c are the transmit chip energy of the uth user and the chip duration, respectively.

The chip block $\{s_u(n);\ n=0\sim N_c-1\}$ can be represented by a vector form as $\mathbf{s}_u=[s_u(0),\ \dots,\ s_u(n),\ \dots,\ s_u(N_c-1)]^T$. N_c-point FFT is carrier out on $\mathbf{s}_u$ to obtain the frequency-domain chip block $\mathbf{S}_u=[S_u(0),\ \dots,\ S_u(k),\ \dots,\ S_u(N_c-1)]^T$ as

$$\mathbf{S}_u=\mathbf{F}\mathbf{s}_u \tag{2}$$

with $\mathbf{F}$ being an $N_c\times N_c$ FFT matrix given as

$$\mathbf{F}=\frac{1}{\sqrt{N_c}}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j2\pi\frac{(1\times1)}{N_c}} & \cdots & e^{-j2\pi\frac{(1\times(N_c-1))}{N_c}} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{-j2\pi\frac{((N_c-1)\times1)}{N_c}} & \cdots & e^{-j2\pi\frac{((N_c-1)\times(N_c-1))}{N_c}} \end{bmatrix}. \tag{3}$$

Tx FDE weight, $\{W_{t,u}(k);\ k=0\sim N_c-1\}$, is multiplied to each component of the frequency-domain transmit chip block $\mathbf{S}_u$ as

$$\mathbf{X}_u=[X_u(0),\ \cdots,\ X_u(k),\ \cdots,\ X_u(N_c-1)]^T=\mathbf{W}_{t,u}\mathbf{S}_u, \tag{4}$$

where $\mathbf{W}_{t,u}=diag\{W_{t,u}(0),\ \dots,\ W_{t,u}(k),\ \dots,\ W_{t,u}(N_c-1)\}$. A constraint of $tr[\mathbf{W}_{t,u}\mathbf{W}_{t,u}^H]=N_c$ is introduced to keep the transmit power intact for u=0~(U–1).

An N_c-point IFFT is applied to $\mathbf{X}_u$ to obtain a time-domain transmit signal $\{x_u(n);\ n=0\sim N_c-1\}$. The time-domain transmit signal block is expressed as $\mathbf{x}_u=[x_u(0),\ \dots,\ x_u(n),\ \dots,\ x_u(N_c-1)]^T=\mathbf{F}^H\mathbf{X}_u$. After the insertion of CP, the signal block is transmitted over a frequency-selective channel.

B. Received signal

We assume that the channels between U users and base station are composed of L distinct paths having different time delays. The channel impulse response between the uth user, u=0~(U–1), and base station is given by

$$h_u(\tau)=\sum_{l=0}^{L-1}h_{u,l}\delta(\tau-\tau_{u,l}), \tag{5}$$

where $h_{u,l}$ and $\tau_{u,l}$ are respectively the complex-valued path gain and the delay time of the lth path, l=0~L–1. Assuming ideal slow transmit power control, $\sum_{l=0}^{L-1}E[|h_{u,l}|^2]=1$.

U users' transmit chip blocks go through different channels. The received signal block $\mathbf{r}=[r(0),\ \dots,\ r(n),\ \dots,\ r(N_c-1)]^T$ after removing the CP is written as

$$\mathbf{r}=\sum_{u=0}^{U-1}\mathbf{h}_u\mathbf{x}_u+\boldsymbol{\eta}, \tag{6}$$

where $\mathbf{h}_u$, u=0~(U–1), is an $N_c\times N_c$ circulant channel impulse response matrix of the uth user and is given by

$$\mathbf{h}_u=\begin{bmatrix} h_{u,0} & & & h_{u,L-1} & \cdots & h_{u,1} \\ h_{u,1} & \ddots & & & \ddots & \vdots \\ \vdots & \ddots & h_{u,0} & \mathbf{0} & & h_{u,L-1} \\ h_{u,L-1} & & h_{u,1} & \ddots & & \\ & \ddots & \vdots & & \ddots & \\ \mathbf{0} & & h_{u,L-1} & \cdots & \cdots & h_{u,0} \end{bmatrix}. \tag{7}$$

$\boldsymbol{\eta}=[\eta(0),\ \dots,\ \eta(n),\ \dots,\ \eta(N_c-1)]^T$ is the noise vector with $\eta(n)$ being a zero-mean additive white Gaussian noise (AWGN) having variance $2N_0/T_c$ (N_0 is the single-sided noise power spectrum density).

N_c-point FFT is carried out on $\mathbf{r}$ to obtain the frequency-domain received signal block $\mathbf{R}=[R(0),\ \dots,\ R(k),\ \dots,\ R(N_c-1)]^T$ as

$$\mathbf{R}=\mathbf{F}\mathbf{r}=\sum_{u=0}^{U-1}\mathbf{H}_u\mathbf{X}_u+\mathbf{N}=\sum_{u=0}^{U-1}\mathbf{H}_u\mathbf{W}_{t,u}\mathbf{S}_u+\mathbf{N}, \tag{8}$$

where $\mathbf{N}=\mathbf{F}\boldsymbol{\eta}$ and

$$\mathbf{H}_u = \mathbf{F}\mathbf{h}_u\mathbf{F}^H = diag\{H_u(0), \ldots, H_u(k), \ldots, H_u(N_c-1)\} \quad (9)$$

with $H_u(k)$ being the channel gain at the kth frequency between the uth user and the base station given by

$$H_u(k) = \sum\nolimits_{l=0}^{L-1} h_{u,l}\exp(-j2\pi k\tau_{u,l}/N_c)\,. \quad (10)$$

At the base station, Rx FDE and successive MUIC are performed iteratively I times. In each iteration stage, U users' decision variables are successively obtained and they are used to generate the ICI & MUI replicas that will be used for performing the following Rx FDE and successive MUIC. Here, Rx FDE and MUIC for the uth user, u=0~(U–1), in the ith iteration stage is considered. Without loss of generality, we assume that ith iteration for 0, 1, …, (u–1)th users have already been completed, while not yet for u, u+1, …, (U–1)th users. After carrying out the ith Rx FDE and MUIC for the uth user, the resultant chip block in frequency-domain is represented as

$$\begin{aligned}\hat{\mathbf{S}}_u^{(i)} &= [\hat{S}_u^{(i)}(0), \;\cdots,\; \hat{S}_u^{(i)}(k), \;\cdots,\; \hat{S}_u^{(i)}(N_c-1)]^T \\ &= \mathbf{W}_{r,u}^{(i)}\mathbf{R} - \sqrt{2E_{u,c}/T_c}\cdot\{\mathbf{W}_{r,u}^{(i)}\mathbf{H}_u\mathbf{W}_{t,u} - \mathbf{I}\}\widetilde{\mathbf{S}}_u^{(i-1)} \\ &\quad - \mathbf{W}_{r,u}^{(i)}\sum_{u'=0}^{u-1}\sqrt{2E_{u,c}/T_c}\cdot\mathbf{H}_{u'}\mathbf{W}_{t,u'}\widetilde{\mathbf{S}}_{u'}^{(i)} \\ &\quad - \mathbf{W}_{r,u}^{(i)}\sum_{u'=u+1}^{U-1}\sqrt{2E_{u,c}/T_c}\cdot\mathbf{H}_{u'}\mathbf{W}_{t,u'}\widetilde{\mathbf{S}}_{u'}^{(i-1)}\end{aligned} \quad , (11)$$

where $\mathbf{W}_{r,u}^{(i)}$=$diag\{W_{r,u}^{(i)}(0), \ldots, W_{r,u}^{(i)}(k), \ldots, W_{r,u}^{(i)}(N_c-1)\}$ is the Rx FDE weight matrix for the uth user in the ith iteration stage. $\{\widetilde{\mathbf{S}}_{u'}^{(i)}$; u'=0~(u–1)} and $\{\widetilde{\mathbf{S}}_{u'}^{(i-1)}$; u'=u~(U–1)} are the frequency-domain transmitted chip block replica of u'th user, where they are generated by the decision variables of the ith and (i–1)th iteration stages, respectively, where $\{\widetilde{\mathbf{S}}_{u'}^{(0)} = \mathbf{0}$; u'=0~(U–1)}. Substituting Eq. (8) into Eq. (11), we obtain

$$\begin{aligned}\hat{\mathbf{S}}_u^{(i)} &= \sqrt{\frac{2E_{u,c}}{T_c}}\mathbf{S}_u + \sqrt{\frac{2E_{u,c}}{T_c}}\{\mathbf{W}_{r,u}^{(i)}\mathbf{H}_u\mathbf{W}_{t,u} - \mathbf{I}\}\{\mathbf{S}_u - \widetilde{\mathbf{S}}_u^{(i-1)}\} \\ &\quad + \mathbf{W}_{r,u}^{(i)}\sum_{u'=0}^{u-1}\sqrt{\frac{2E_{u',c}}{T_c}}\mathbf{H}_{u'}\mathbf{W}_{t,u'}\{\mathbf{S}_{u'} - \widetilde{\mathbf{S}}_{u'}^{(i)}\} \\ &\quad + \mathbf{W}_{r,u}^{(i)}\sum_{u'=0}^{u-1}\sqrt{\frac{2E_{u',c}}{T_c}}\mathbf{H}_{u'}\mathbf{W}_{t,u'}\{\mathbf{S}_{u'} - \widetilde{\mathbf{S}}_{u'}^{(i-1)}\} + \mathbf{W}_{r,u}^{(i)}\mathbf{N},\end{aligned} \quad (12)$$

where the first is the desired chip block, second is the residual ICI, and third and fourth terms are the residual MUIs, respectively. The decision variable for the uth user in the ith iteration stage is obtained by performing N_c-point IFFT to $\hat{\mathbf{S}}_u^{(i)}$ as $\hat{\mathbf{s}}_u^{(i)} = [\hat{s}_u^{(i)}(0), \;\cdots,\; \hat{s}_u^{(i)}(n), \;\cdots,\; \hat{s}_u^{(i)}(N_c-1)]^T = \mathbf{F}^H\hat{\mathbf{S}}_u^{(i)}$. Then, the DS-CDMA despreading is carried out as

$$\hat{d}_u^{(i)}(m) = \frac{1}{SF}\sum_{n=mSF}^{(m+1)SF}\hat{s}_u^{(i)}(n)c_u^*(n)\,. \quad (13)$$

The frequency-domain soft chip block replica $\widetilde{\mathbf{S}}_u^{(i)} = [\widetilde{S}_u^{(i)}(0), \;\cdots,\; \widetilde{S}_u^{(i)}(k), \;\cdots,\; \widetilde{S}_u^{(i)}(N_c-1)]^T$ in Eq. (11) is computed in a same way as [10,11]. The LLR of the transmitted bit sequence is computed using the decision variables of Eq. (13). Then, it is used for generating the data symbol replica $\{\widetilde{d}_u^{(i)}(m)$; m=0~N_c/SF–1} and the resultant replica is spread to generate the chip block replica. The chip block replica is transformed into frequency-domain chip block replica by the N_c-point FFT in order to compute the MUI replica for the other users and the residual ICI replica for the uth user itself in the next iteration.

The successive detection of U users is iterated I times.

III. DERIVATION OF TX AND RX FDE WEIGHTS

In this section, we derive the set of FDE weights that aims to minimize MSE. First, we derive Rx FDE weight for the uth user in the ith iteration stage, $\mathbf{W}_{r,u}^{(i)}$, for the given channel gains and Tx FDE weights of users, $\mathbf{W}_{t,u}$, u=0~(U–1). Each user has to fix $\mathbf{W}_{t,u}$ before transmitting the signal. In [12], we derived optimal Tx FDE weight for the given Rx FDE weight that minimizes MSE. However, since Rx FDE weight changes in the iteration process according to the power of the residual ICI & MUI [10] in this scheme, it is difficult to give $\mathbf{W}_{t,u}$. Therefore, we assume that each user predicts Rx FDE weight in the final iteration stage, $\mathbf{W}_{r,u}^{(I-1)}$, and computes Tx FDE weight for the given predicted Rx FDE weight. The detailed derivation is as follows.

A. *Rx FDE weight for the uth user in the ith iteration stage*

The error vector between the transmitted and equalized chip blocks for the uth user in the ith iteration stage is defined as

$$\mathbf{e}_u^{(i)} = \mathbf{S}_u^{(i)} - \hat{\mathbf{S}}_u^{(i)}/\sqrt{2E_{u,c}/T_c}\,. \quad (14)$$

The total MSE of the chip block is given by

$$\begin{aligned}e_u^{(i)} &= tr[E(\mathbf{e}_u^{(i)}\mathbf{e}_u^{(i)H})] \\ &= \rho_u^{(i-1)}tr[\{\mathbf{W}_{r,u}^{(i)}\mathbf{H}_u\mathbf{W}_{t,u} - \mathbf{I}\}\{\mathbf{W}_{r,u}^{(i)}\mathbf{H}_u\mathbf{W}_{t,u} - \mathbf{I}\}^H] \\ &\quad + \sum_{u'<u}\frac{E_{u',c}}{E_{u,c}}\rho_{u'}^{(i)}tr[\mathbf{W}_{r,u}^{(i)}\mathbf{H}_{u'}\mathbf{W}_{t,u'}\mathbf{W}_{t,u'}^H\mathbf{H}_{u'}^H\mathbf{W}_{r,u}^{(i)H}] \\ &\quad + \sum_{u'>u}\frac{E_{u',c}}{E_{u,c}}\rho_{u'}^{(i-1)}tr[\mathbf{W}_{r,u}^{(i)}\mathbf{H}_{u'}\mathbf{W}_{t,u'}\mathbf{W}_{t,u'}^H\mathbf{H}_{u'}^H\mathbf{W}_{r,u}^{(i)H}] \\ &\quad + \frac{N_0}{E_{u,c}}tr[\mathbf{W}_{r,u}^{(i)}\mathbf{W}_{r,u}^{(i)H}],\end{aligned} \quad (15)$$

where in the above, $\rho_u^{(i-1)}$, $\{\rho_{u'}^{(i)}$; u'<u}, and $\{\rho_{u'}^{(i-1)}$; u'>u} represent the powers of the residual ICI, the MUI from the

u'($<u$)th users, and the MUI from the u'($>u$)th users, respectively. $\rho_{u'}^{(i)}$ is given as [13]

$$\rho_{u'}^{(i)} = E[|S_{u'}(k) - \tilde{S}_{u'}^{(i)}(k)|^2] \approx \frac{SF}{N_c} \sum_{n=0}^{N_c/SF-1} \{1 - |\tilde{d}_{u'}^{(i)}(n)|^2\} \quad (16)$$

for u=0~U–1 when QPSK data modulation is used.

The Rx FDE weight for the uth user in the ith iteration stage satisfies

$$\partial e_u^{(i)} / \partial \mathbf{W}_{r,u}^{(i)} = \mathbf{0} \quad (17)$$

and hence, it is given by

$$\begin{aligned} \mathbf{W}_{r,u}^{(i)} = \rho_u^{(i-1)} \mathbf{W}_{t,u}^H \mathbf{H}_{u'}^H \times \Bigg\{ & \sum_{u'<u} \frac{E_{c,u'}}{E_{c,u}} \rho_{u'}^{(i)} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H \\ & + \sum_{u' \geq u} \frac{E_{c,u'}}{E_{c,u}} \rho_{u'}^{(i-1)} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H + \frac{N_0}{E_{c,u}} \mathbf{I} \Bigg\}^{-1}. \end{aligned} \quad (18)$$

B. *Tx FDE weight for the uth user*

The Rx FDE weight changes through the iterative process. Therefore, we introduce the prediction of the Rx FDE weight when the iterative process terminates, similar to [6].

According to Eq. (18), variables in the iteration process are $\{\rho_{u'}^{(i)}$; u'=0~(u–1)} and $\{\rho_{u'}^{(i-1)}$; u'=u~(U–1)}. Therefore, the transmitter predicts these variables in the final iteration stage. We introduce the predicted values of them as $\{\phi_{u'}$; u'=0~(U–1)}. The predicted Rx FDE weight for the uth user can be written as

$$\begin{aligned} \mathbf{W}_{r,u}^{tx} = \phi_u \mathbf{W}_{t,u}^H \mathbf{H}_{u'}^H \times \Bigg\{ & \sum_{u'<u} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H \\ & + \sum_{u' \geq u} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H + \frac{N_0}{E_{c,u}} \mathbf{I} \Bigg\}^{-1}. \end{aligned} \quad (19)$$

Replacing $\mathbf{W}_{r,u}^{(i)}$ of Eq. (15) by $\mathbf{W}_{r,u}^{tx}$ of Eq. (19) gives the MSE corresponding to the uth user's prediction as

$$\begin{aligned} e_u^{(tx)} = \phi_u \cdot tr \Bigg[& \left\{ \sum_{u' \neq u} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H + \frac{N_0}{E_{c,u}} \mathbf{I} \right\} \\ & \times \left\{ \sum_{u'} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} \mathbf{H}_{u'} \mathbf{W}_{t,u'} \mathbf{W}_{t,u'}^H \mathbf{H}_{u'}^H + \frac{N_0}{E_{c,u}} \mathbf{I} \right\}^{-1} \Bigg]. \end{aligned} \quad (20)$$

Therefore, the problem formulation for deriving Tx FDE weight of the uth user is given as

$$\min \ e_u^{(tx)} = \phi_u \sum_{k=0}^{N_c-1} \frac{\displaystyle\sum_{\substack{u'=0 \\ \neq u}}^{U-1} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} |H_{u'}(k)|^2 |W_{t,u'}(k)|^2 + \frac{N_0}{E_{c,u}}}{\displaystyle\sum_{u'=0}^{U-1} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} |H_{u'}(k)|^2 |W_{t,u'}(k)|^2 + \frac{N_0}{E_{c,u}}} \quad (21)$$

$$\text{s.t.} \quad \sum_{k=0}^{N_c-1} |W_{t,u}(k)|^2 = N_c.$$

Solving the above, we obtain

$$|W_{t,u}(k)|^2 = \max \left[\frac{1}{\sqrt{\mu}} \frac{\sqrt{\displaystyle\sum_{u' \neq u} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} |H_{u'}(k)|^2 |W_{t,u'}(k)|^2 + \frac{N_0}{E_{c,u}}}}{|H_u(k)|} - \frac{\displaystyle\sum_{u' \neq u} \frac{E_{c,u'}}{E_{c,u}} \phi_{u'} |H_{u'}(k)|^2 |W_{t,u'}(k)|^2 + \frac{N_0}{E_{c,u}}}{\phi_u |H_u(k)|^2}, \ 0 \right], \quad (22)$$

where μ is determined so as to satisfy the transmit power constraint.

Eq. (22) indicates that the derived Tx FDE weight for the uth user, $W_{t,u}(k)$, is a function not only of $H_u(k)$ and ϕ_u but also of {$H_{u'}(k)$ and $W_{t,u'}(k)$; $u'\neq u$} and {$\phi_{u'}$; $u'\neq u$}. This means that if the MUI at a frequency is very large, the Tx FDE weight of the uth user at the frequency should be 0 to avoid the negative effect of the strong MUI. However, the user cannot estimate other users' channel gains. Furthermore, the Tx FDE weights of users interact with each other.

In this paper, we relax this unrealistic condition; each user predicts that the MUI for the user can always be perfectly cancelled at the base station, i.e., for the uth user, $\phi_{u'}$=0 for $u'\neq u$. Under this prediction, Eq. (22) can be simplified as

$$|W_{t,u}(k)|^2 = \max \left[\frac{1}{\sqrt{\mu}} \frac{\sqrt{(E_{c,u}/N_0)^{-1}}}{|H_u(k)|} - \frac{(E_{c,u}/N_0)^{-1}}{\phi_u |H_u(k)|^2}, \ 0 \right] \quad (23)$$

which is not a function of other users' channel gains and is identical to the Tx FDE weight for the case of downlink [6].

IV. PERFORMANCE EVALUATION

Computer simulation is conducted to verify the effectiveness of the proposed scheme. We assume that the channel is L=16-path frequency-selective block Rayleigh fading having uniform power delay profile. Uncoded QPSK data transmission is considered. FFT/IFFT block size N_c=256 and CP-length N_g=32 are assumed. SF=16. Slow transmit power control is considered, i.e., chip energy for all the users is assumed to be the same. Optimal $\{\phi_u$; u=0~(U–1)} are found through preliminary computer simulation that minimizes average BER for the given average transmit $E_{c,u}/N_0$ and the channel power delay profile.

Figure 2 illustrates the achievable average BER with the proposed scheme when the transmit bit energy-to-noise power spectrum density ratio $E_b/N_0(=0.5SFE_c/N_0(1+N_g/N_c))$=8dB as a function of the number of multi-access users, U. The achievable BER with the conventional scheme [10,11] is also plotted for comparison. The average BER degrades as the number of multi-access users increases. Without cancellation, the BER is very high and BER<10^{-3} is not able to be achieved for both the proposed and conventional schemes. On the other hand, when I=5, better BER performance can be achieved by suppressing the residual ICI and MUI due to the iterative process. Especially in the proposed scheme, with the help of the Tx FDE at each user, much improved BER can be achieved. For instance, for achieving BER=10^{-3}, while the allowable number of users in the conventional scheme with I=5 is only 3, that in the proposed scheme with I=5 is 9.

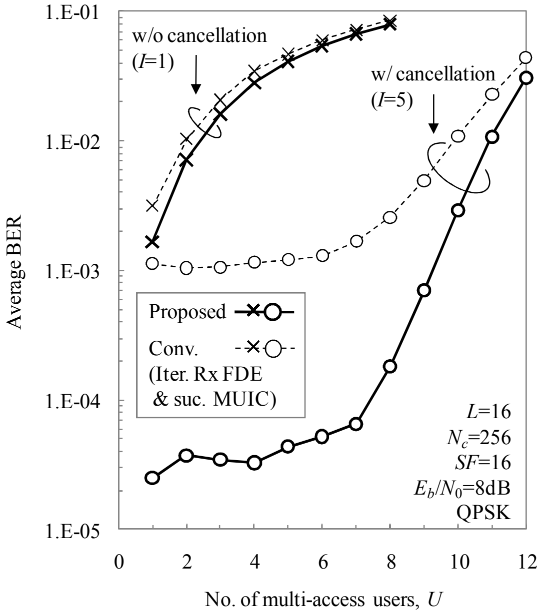


Fig.2 Average BER versus U.

V. CONCLUSION

In this paper, we proposed the joint Tx/iterative Rx MMSE-FDE and successive MUIC suitable for uplink DS-CDMA. In the proposed scheme, one-tap Rx FDE and successive MUIC are performed at the base station in an iterative manner, while simple one-tap Tx FDE is performed at users. We derived the set of Tx and Rx FDE weights based on the MMSE criterion. The achievable BER performance in a frequency-selective Rayleigh fading was evaluated by the computer simulation. It was shown that the proposed scheme is capable of accommodating 3 times larger number of users than the conventional scheme.

The proposed scheme requires CSI at the transmitter side. Another uplink multi-access scheme that uses CSI at the user side is single-carrier (SC) frequency-division multi-access (FDMA) with precoding [14], which is adopted for the uplink of long-term evolution (LTE)-advanced systems. Performance comparison between the proposed scheme and SC-FDMA with precoding is left as an important future study topic.

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