Multiuser Channel Estimation for CDMA Systems over Doubly Selective Fading Channels

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***Abstract*—In this paper, a pilot assisted minimum mean square error multiuser channel estimation algorithm is proposed for quasi-synchronous CDMA systems. The doubly selective multiuser fading channel is represented as a time-varying chip-spaced tapped delay line filter with *correlated* filter taps. The multiuser channel tap coefficients at pilot symbol positions are estimated under the MMSE criterion with the help of the channel tap correlation matrix, which can be jointly estimated with the filter tap timing with a novel iterative method. Simulations show that the channel tap correlation is critical to the performance of the channel estimation, and the channel taps at different delays cannot be assumed uncorrelated for systems experiencing doubly selective fading.**

I. Introduction

Code division multiple access (CDMA) technique has emerged as a promising multiple access scheme for wireless communication systems. The topic of channel estimation for CDMA systems has received considerable attentions in the literature [2]-[6]. Most of the previous works assumed that the transmit filer and receive filter are rectangular waveforms with a single chip duration, which is quite different from the bandwidth-limited root-raised cosine pulses adopted by the current and emerging CDMA wireless systems such as IS-95, cdma2000 and UMTS [7]. The rectangular shaping pulse assumption certainly leads to simple system models, but it implies unlimited bandwidth. Additionally, it is commonly assumed that the fading channels can be represented as tapped delay line filters whose taps are statistically uncorrelated [4], [5]. However, it was recently shown in [8] when the doubly selective fading passes through the bandwidth-limited receive filter, the equivalent discrete-time time-varying channel taps are generally correlated. This correlation can affect the system performance dramatically if it is not carefully taken.

In this paper, we focus on the multiuser channel estimation for quasi-synchronous CDMA (QS-CDMA)[1] systems under a doubly selective fading environment. The composite fading channel response, which combines the effects of the transmit filter, the physical fading channel and the receive filter, is represented as a tapped delay line filter with *correlated* tap coefficients. Moreover, we will show that the channel tap correlation is critical to the performance of the channel estimation. Utilizing the channel tap correlation information, we propose a pilot assisted MMSE multiuser channel estimation algorithm, and the channel tap correlation is treated as an essential factor in the development of the algorithm. An iterative method is proposed for the joint estimation of the channel correlation and the channel tap timing based on the received samples, and these parameters are used to form the MMSE algorithm.

[1] In a QS-CDMA system, the uncertainty of the relative transmission delay of each user is limited to a few chip periods, which can be achieved with the use of a GPS receiver at the base station, [5].

II. Discrete-time System Model

A discrete-time model of the multiuser CDMA system is described in this section. We consider the up-link of a multiuser CDMA system consisting of M users. The transmitted signal $s_m(t)$ of the mth user is given by

$$s_m(t) = \sqrt{\frac{P_m}{N}} \sum_{i=-\infty}^{+\infty} \sum_{k=0}^{N-1} b_m(i) c_m(k) p(t - iT_s - kT_c), \quad (1)$$

where P_m is the average transmit power of the mth user, N is the processing gain, T_c is the chip period, $T_s = NT_c$ is the symbol period, $\mathbf{c}_m = [c_m(0), c_m(1), \cdots, c_m(N-1)]^T \in \mathbb{C}^{N\times 1}$ is the mth user's spreading code [2], $b_m(i)$ is the ith transmit data (or pilot) symbol, and $p(t)$ is the normalized root raised cosine (RRC) filter. In a system with pilot symbol assisted modulation (PSAM), the transmit symbols $b_m(i)$ are divided into slots, with the pilot symbols being distributed within each slot.

Let $g_m(t,\tau)$ be the time-varying fading channel impulse response for the mth user, then at the base station, the received signal $r(t)$ is the superposition of the fading distorted signals from all the M users plus the additive noise,

$$r(t) = \sum_{m=1}^{M} s_m(t - \Delta_m) \circledast g_m(t,\tau) + v(t), \quad (2)$$

where $\circledast$ denotes the convolution operation, Δ_m is the differential transmission delay experienced by the mth user, and $v(t)$ is the additive white Gaussian noise (AWGN) with variance N_0. For a quasi-synchronous system, the relative delay Δ_m is assumed to be uniformly distributed within $[-DT_c, +DT_c]$ with $D \ll N$ [5]. The received signal $r(t)$ is passed through the receive filter $p^*(-t)$, and the output is $y(t) = r(t) \circledast p^*(-t)$. If we define the mth user's composite impulse response (CIR) as

[2] The normalized signature waveform of the mth user is given by $w_m(t) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} c_m(k) p(t - kT_c)$.

$$h_m(t,\tau) \;=\; \int_{-\infty}^{+\infty} R_{pp}(\tau-\Delta_m-\alpha)g_m(t,\alpha)d\alpha, \tag{3}$$

where $R_{pp}(t)=\int_{-\infty}^{\infty} p(t+\tau)p^*(\tau)d\tau$, then the chip-rate sampled output of the matched filter can be written by

$$y_j(n) \;=\; \sqrt{\frac{P_m}{N}} \sum_{m=1}^{M} \sum_{i=-\infty}^{+\infty} \sum_{l=-\infty}^{+\infty} b_m(i)\cdot c_m[(j-i)N+(n-l)] \times h_m(j,l)+z_j(n), \quad \text{for } n=0,1,\cdots,N-1;\;\; j=1,2,\cdots \tag{4}$$

where $y_j(n)$ is the nth chip-rate sample of jth data symbol of $y(t)$ and $z_j(n)$ is the chip-rate sample of $z(t)=v(t)\circledast p^*(-t)$ at the time instant $t=jT_s+nT_c$. Likewise, $h_m(j,l)=h_m(jT_s,lT_c)$ is the discrete-time version of the CIR $h_m(t,\tau)$, and we used $l=(j-i)N+(n-k)$ in (4). The noise component $z_j(n)$ is still AWGN with variance N_0 because the chip matched filter $p^*(-t)$ is normalized RRC filter. It is assumed here that the channel varies slow enough that it remains constant during one symbol duration, which is a commonly used mild assumption.

To simplify the representation of (4), we note that the chip index k of $c_m(k)$ satisfies $0\le k<N$. Combining this inequality with $k=(j-i)N+(n-l)$, we can immediately get

$$j+\frac{n-l}{N}-1<i\le j+\frac{n-l}{N}, \tag{5}$$

where i is the symbol index of the transmitted symbol $b_m(i)$, and it can only take integer values. In the range of i described in (5), there exists one and only one integer value, which must be $i=j+\lfloor\frac{n-l}{N}\rfloor$, where $\lfloor\cdot\rfloor$ denotes rounding to the nearest smaller integer. Substituting the value of i to $k=(j-i)N+(n-l)$, we can get

$$k=-\lfloor\frac{n-l}{N}\rfloor N+(n-l)=(n-l)_N, \tag{6}$$

where $(x)_N$ can be viewed as the residue of x/N with $0\le(x)_N\le N-1$. The above analysis leads to a simplified representation of (4)

$$y_j(n) \;=\; \sqrt{\frac{P_m}{N}} \sum_{m=1}^{M} \sum_{l=-\infty}^{+\infty} b_m\left(j+\lfloor\frac{n-l}{N}\rfloor\right)\cdot c_m\left[(n-l)_N\right] \times h_m(j,l)+z_j(n). \tag{7}$$

The relationship of j, n and l is illustrated in Fig. 1, where the lth delayed version of the transmitted symbols is given as an example, and the corresponding sampling time is $t=jT_s+(n-l)T_c$.

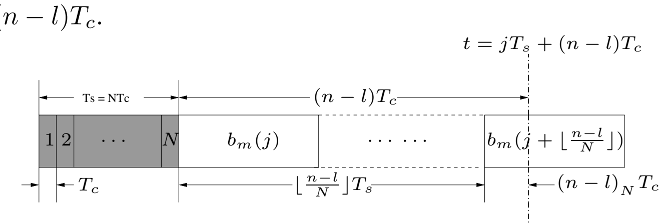

Fig. 1. The lth delayed version of the transmitted symbols

Eqn. (7) is a discrete-time representation of the multiuser CDMA system, and the doubly selective fading channel is represented as a T_c-spaced tapped delay line filter. With the definition of the CIR given by (3), it is demonstrated in [8] that the channel tap coefficients $h_m(j,l_1)$ and $h_m(j,l_2)$ are mutually correlated zero-mean Gaussian processes in a Rayleigh fading channel. If the physical channel $g_m(t,\tau)$ experiences wide-sense stationary uncorrelated scattering fading, the correlation function $\rho_m(l_1,l_2)=E[h_m(j,l_1)h_m^*(j,l_2)]$ can be expressed as follows [8]

$$\rho_m(l_1,l_2)=\int_{-\infty}^{+\infty} R_{pp}(l_1T_c-\mu)R_{pp}^*(l_2T_c-\mu)G_m(\mu-\Delta_m)d\mu, \tag{8}$$

where $G_m(\mu)$ is the normalized power delay profile of the channel. It should be noted that the discrete-time channel model presented here is different from those used in [4] and [5], where the channel coefficients of different delayed taps are assumed mutually uncorrelated. We will show that the correlation between the channel taps is critical to the performance of the channel estimation and can be exploited to enhance estimation accuracy.

With the definition of $\rho_m(l_1,l_2)$, the power of the lth channel tap is $\rho(l,l)$, which is jointly determined by $G_m(\mu)$ and $R_{pp}(t)$. Since the time-domain tails of $p(t)$ falls off rapidly, $\rho(l,l)$ will decrease quickly with the increase of $|l|$. When $\rho(l,l)$ is smaller than a pre-defined threshold, it has very little impact on the output signal, and thus can be discarded. Without loss of generality, we use $\mathbf{l}_m=[-L_{m1},\cdots,L_{m2}]^T\in\mathbb{I}^{\lambda_m\times 1}$ to represent the tap delay index vector of the mth user, where L_{m1} and L_{m2} are non-negative integers. With $\mathbf{l}_m$, we define the multiuser channel tap coefficients vector $\mathbf{h}(j)$ as

$$\mathbf{h}(j) \;=\; [\mathbf{h}_1(j)^T,\mathbf{h}_2(j)^T,\cdots,\mathbf{h}_M(j)^T]^T, \tag{9}$$

where $\mathbf{h}_m(j)=[h_m(j,-L_{m1}),\cdots,h_m(j,L_{m2})]^T$, and $(\cdot)^T$ denotes matrix transpose. With this representation of the discrete-time model, the necessary knowledge of the multiuser channel is the set of time-varying coefficients characterizing each path of the channel, and the problem of multiuser channel estimation is converted to the estimation of the time-varying channel coefficients $h_m(j,l)$ and the delay index vector $\mathbf{l}_m$.

III. MMSE-BASED MULTIUSER CHANNEL ESTIMATION

In this section, we focus on the estimation of the channel coefficients at pilot positions, which will be interpolated to obtain the time-varying channel coefficients over one entire slot. In order to exploit the channel tap correlation information, the proposed algorithm is based on the MMSE criterion, which is capable of utilizing and preserving the correlation information of the fading channel.

We assume that the physical fading channels of different users are uncorrelated to each other, then the multiuser channel tap correlation matrix $\mathbf{R}_h=E[\mathbf{h}(j)\mathbf{h}^H(j)]=\text{diag}(\mathbf{R}_{h_1},\cdots,\mathbf{R}_{h_M})$ is a block-diagonal matrix, with the mth diagonal block $\mathbf{R}_{h_m}=E[\mathbf{h}_m(j)\mathbf{h}_m^H(j)]\in\mathbb{C}^{\lambda_m\times\lambda_m}$ given by

$$\mathbf{R}_{h_m}=\begin{bmatrix}\rho_m(-L_{m1},-L_{m1}) & \cdots & \rho_m(-L_{m1},L_{m2})\\ \vdots & \ddots & \vdots\\ \rho_m(L_{m2},-L_{m1}) & \cdots & \rho_m(L_{m2},L_{m2})\end{bmatrix}. \tag{10}$$

It can be seen from (8) and (10) that the channel tap correlation matrix $\mathbf{R}_h$ is a function of $G_m(\mu)$, Δ_m, and $\mathbf{l}_m$, which are usually unavailable at the receiver. Therefore, $\mathbf{R}_h$ is usually not known to the receiver. In this section, we focus on the formulation of the MMSE-based channel estimation algorithm. The estimation of $\mathbf{R}_h$ will be discussed in the next section.

For a QS-CDMA system, it is assumed that all the users are slot synchronized, and the received signals at pilot positions are the superposition of the faded pilot symbols of all the users. For convenience of representation, the symbol '1' is used as pilot symbols. According to (7), the received samples contributed exclusively by pilot symbols can be written as

$$\mathbf{y}(j_p) = \mathbf{C}\mathbf{h}(j_p) + \mathbf{z}(j_p), \tag{11}$$

where $\mathbf{y}(j_p) = [y_{j_p}(0), \cdots, y_{j_p}(N-1)]^T$, $\mathbf{z}(j_p) = [z_{j_p}(0), \cdots, z_{j_p}(N-1)]^T$, and the multiuser code matrix $\mathbf{C}$ is

$$\begin{aligned} \mathbf{C} &= [\mathbf{C}_1 \vdots \mathbf{C}_2 \vdots \cdots \vdots \mathbf{C}_M] & (12)\\ \text{with } \mathbf{C}_m &= [\mathbf{c}_m(-L_{m1}), \cdots, \mathbf{c}_m(L_{m2})], & (13)\end{aligned}$$

where $\mathbf{c}_m(i) = [c_m(N-i), \cdots, c_m(N-1), c_m(0), \cdots, c_m(N-i-1)]^T$ is obtained from circularly shifting i symbols of the original code vector $\mathbf{c}_m$. It is important to note that the multiuser code matrix $\mathbf{C}$ is determined by both the spreading codes and the tap delay index vector $\mathbf{l}_m$. For a multiuser detector, the spreading codes are known to the base station, while $\mathbf{l}_m$ needs to be estimated. We will show in the next section that $\mathbf{l}_m$ can be jointly estimated with $\mathbf{R}_h$ based on a novel iterative method.

We are now in a position to present our MMSE-based channel estimation algorithm as follows.

Theorem 1: The MMSE estimation of the multiuser channel tap coefficients $\mathbf{h}(j_p)$ at pilot symbol positions is given by

$$\hat{\mathbf{h}}(j_p) = \mathbf{R}_h\mathbf{C}^H \cdot \left[\mathbf{C}\mathbf{R}_h\mathbf{C}^H + N_0\mathbf{I}_N\right]^{\dagger} \cdot \mathbf{y}(j_p), \quad \text{for } p = 1, 2, \cdots, N_p, \tag{14}$$

where $(\cdot)^{\dagger}$ represents the matrix pseudo-inverse for an ill-conditioned matrix, or matrix inverse for a full-rank matrix, j_p is the position index of the pth pilot symbol in a slot with N_p pilot symbols, $\hat{\mathbf{h}}(j_p)$ is the estimated multiuser channel tap coefficients, and $\mathbf{I}_N$ is an $N \times N$ identity matrix,

Proof: Define the MMSE cost function as follows

$$\phi = E\left\{ [\mathbf{h}(j_p) - \hat{\mathbf{h}}(j_p)]^H [\mathbf{h}(j_p) - \hat{\mathbf{h}}(j_p)] \Big| \mathbf{y}(j_p), \mathbf{C} \right\}. \tag{15}$$

The coefficients vector $\hat{\mathbf{h}}(j_p)$ that minimizes ϕ can be obtained from the equation $\frac{\partial \phi}{\partial \hat{\mathbf{h}}(j_p)} = 0$, and the solution to the partial differential equation can be written as

$$\hat{\mathbf{h}}(j_p) = E\left[\mathbf{h}(j_p)\mathbf{y}^H(j_p)\right] \cdot \left\{E\left[\mathbf{y}(j_p)\mathbf{y}^H(j_p)\right]\right\}^{\dagger} \mathbf{y}(j_p). \tag{16}$$

From (11) and the fact that $z_j(n)$ is AWGN with variance N_0, we can get

$$\begin{aligned} E[\mathbf{y}(j_p)\mathbf{y}^H(j_p)] &= \mathbf{C}\mathbf{R}_h\mathbf{C}^H + N_0\mathbf{I}_N, \\ E[\mathbf{h}(j_p)\mathbf{y}^H(j_p)] &= \mathbf{R}_h\mathbf{C}^H, & (17)\end{aligned}$$

Substitute (17) in (16), we get (14). ■

To fulfill the MMSE solution described in Theorem 1, we need to know the multiuser channel correlation matrix $\mathbf{R}_h$, the delay index vector $\mathbf{l}_m$, and the additive noise variance N_0. The estimation of these parameters is discussed in the next section.

IV. MMSE-Parameter Estimation

In this section, N_0 is estimated by exploiting the eigen structure of the received signals. Likewise, the matrix $\mathbf{R}_h$ and the vector $\mathbf{l}_m$ are jointly estimated by a novel iterative method.

A. Estimation of the Additive Noise Variance N_0

The variance N_0 of the additive noise component $\mathbf{z}(j)$ can be extracted from the received data symbols $\mathbf{y}(j)$ with the method presented in [3].

As shown in [3], the noise variance N_0 is equal to the smallest $N - M$ eigen values of the correlation matrix $\mathbf{R}_y = E[\mathbf{y}(j)\mathbf{y}^H(j)]$. Therefore, an estimation of N_0 can be obtained as the average of the smallest $N-M$ eigen values of $\mathbf{R}_y$. The correlation matrix $\mathbf{R}_y$ can be estimated from the received data samples as $\widehat{\mathbf{R}}_y = \frac{1}{J}\sum_{j=1}^{J} \mathbf{y}(j)\mathbf{y}^H(j)$, where J is the number of symbols in one slot. It is apparent that the larger the value of J is, the more accurate the estimation of $\mathbf{R}_y$. To increase the estimation accuracy, several consecutive slots can be used to form a hyper-slot in the estimation. After $\widehat{\mathbf{R}}_y$ is obtained, we can perform the eigen value decomposition of it, and the average of the smallest $N-M$ eigen values is the estimated value of N_0.

B. Joint Estimation of $\mathbf{R}_h$ and $\mathbf{l}_m$

In this subsection, an iterative method is proposed for the joint estimation of the multiuser channel tap correlation matrix $\mathbf{R}_h$ and tap delay index vector $\mathbf{l}_m$. The elements of $\mathbf{R}_h$ are mainly determined by the relative transmission delay Δ_m and the power delay profile $G_m(\mu)$. In the tapped delay line representation of the fading channel, the effects of Δ_m and the delay spread of $G_m(\mu)$ are incorporated into the T_c-spaced tap delay index vector $\mathbf{l}_m$. Therefore $\mathbf{R}_h$ and $\mathbf{l}_m$ are interacted to each other, and this interaction can be utilized for the joint estimation of $\mathbf{R}_h$ and $\mathbf{l}_m$. It is pointed out here that our algorithm does not need to estimate $G_m(\mu)$ and Δ_m.

The interactions between $\mathbf{R}_h$ and $\mathbf{l}_m$ can be explored via the help of the statistical properties of the received pilot samples. According to (11), the correlation matrix $\mathbf{R}_{y_p} = E[\mathbf{y}(j_p)\mathbf{y}(j_p)^H]$ of the received pilot symbols can be written by

$$\mathbf{R}_{y_p} = \mathbf{C}\mathbf{R}_h\mathbf{C}^H + N_0\mathbf{I}_N. \tag{18}$$

In the equation above, the noise variance N_0 can be obtained from the method described in Section IV-A, $\mathbf{R}_{y_p}$ can be estimated from the received pilot symbols as $\widehat{\mathbf{R}}_{y_p} = \frac{1}{N_p}\sum_{p=1}^{N_p} \mathbf{y}(j_p)\mathbf{y}^H(j_p)$, while $\mathbf{R}_h$ and the code matrix $\mathbf{C}$ are two unknown matrices to be determined. From the definition of $\mathbf{C}$ in (13), we can see that $\mathbf{C}$ is determined by both the spreading codes and the vector $\mathbf{l}_m = [-L_{m1}, \cdots, L_{m2}]^T$. As discussed in Section II, the vector $\mathbf{l}_m$ is obtained by discarding the channel taps with power smaller than a certain threshold, and the channel tap power $E[h_m(j,l)h_m^*(j,l)] = \rho_m(l,l)$ can be found from the diagonal of $\mathbf{R}_h$. If we know the power of all the possible channel taps, then we can obtain $\mathbf{l}_m$ by discarding the negligible taps. Furthermore, when $\mathbf{l}_m$ is known, we can form the code matrix $\mathbf{C}$, with which $\mathbf{R}_h$ can be computed from (18).

Based on the reciprocal relationship between $\mathbf{R}_h$ and $\mathbf{l}_m$, an iterative method is proposed for the joint estimation of these two parameters.

Algorithm: Joint estimation of the multiuser channel tap correlation matrix $\mathbf{R}_h$ and the tap delay index vector $\mathbf{l}_m$.

Step I: Set the initial value of the delay index vector as $\mathbf{l}_m = [-D-1, L_{m0}+D]$ [3], where D is the maximum transmission delay factor, and $L_{m0} \approx \tau_{max}^{(m)}/T_c$ with $\tau_{max}^{(m)}$ being the maximum possible delay spread of the mth user's physical channel.

Step II: Based on the current value of $\mathbf{l}_m$, construct the multiuser code matrix $\mathbf{C}$ according to (13). With the estimated value of $\mathbf{R}_{y_p}$, N_0, and the current value of $\mathbf{C}$, compute $\mathbf{R}_h$ as follows

$$\mathbf{R}_h = \mathbf{C}^{\dagger}(\mathbf{R}_{y_p} - N_0\mathbf{I}_N)(\mathbf{C}^H)^{\dagger}. \tag{19}$$

Step III: With the diagonal elements of $\mathbf{R}_h$ obtained from Step II, find the maximum power taps for each user, and represent the maximum tap power of the mth user as $\mathcal{P}_m$. For all the taps of the mth user, discard the taps with power smaller than $\eta \cdot \mathcal{P}_m$, with $0 < \eta < 1$ being a pre-defined threshold.

Step IV: After discarding the negligible taps for each user, a new tap delay index vector $\mathbf{l}_m$ for each user can be formed, and go back to Step II. If there are no more taps to discard, or the maximum number of iterations is reached, then the current values of $\mathbf{R}_h$ and $\mathbf{l}_m$ are the desired values.

With the proposed iterative method, the value of $\mathbf{R}_h$ and $\mathbf{l}_m$ can be jointly estimated from the received pilot samples for each slot. When we set $\eta = 1\%$, simulations show that the iterative method usually converges within 2 iterations, and it leads to accurate estimations of $\mathbf{R}_h$ and $\mathbf{l}_m$.

The time-varying channel coefficients of one entire slot can be obtained by interpolating the MMSE-estimated CIR at pilot positions. Here we adopt a sub-optimum constant matrix interpolation method [10] for channel interpolation, since it donesn't require the knowledge of the time correlation of the time-varying channel, and details are omitted here for brevity.

V. Simulation Results

A. System Configurations

In the simulation, each slot has 4 head pilot symbols and 2 tail pilot symbols with 56 data symbols in the middle. The time duration of each slot is $2ms$, and every 2 slots are combined as a hyper-slot in the estimation. Gold sequences with processing gain of $N = 127$ are used as the spreading codes. The chip rate of the system is chosen to be 3.84 Mcps. The transmitted data are QPSK modulated. RRC filter with rolloff factor of 0.22 is used as both the transmit filter and the chip matched filter. Vehicular A propagation profile [7] is chosen to be the power delay profile $G_m(\tau)$ for simulations with the normalized Doppler frequency set to $f_d T_{slot} = 0.1$. The relative transmission delay Δ_m of each user is uniformly distributed in $[-DT_c, DT_c]$. Unless otherwise stated, we set $D = 3$ in the simulations. In the iterative estimation of $\mathbf{R}_h$ and $\mathbf{l}_m$, the maximum number of iterations are set to 2, and the discarding threshold factor η is set to 1%. A successive interference canceller [1] is employed for coherent multiuser detection.

[3]We choose $-D-1$ as the smallest index because the absolute amplitude of the RRC filter is very small for samples one period away from the peak value.

B. Performance Evaluation

The effectiveness of the estimation for $\mathbf{R}_h$ and $\mathbf{l}_m$ are demonstrated by the bit error rate (BER) performance of a 5-user CDMA system. In Fig. 2, four cases are depicted for comparisons. The first case is the BER performance of the system with perfect knowledge of the multiuser channels. The second case is the BER of the system with knowledge of the correlation matrix $\mathbf{R}_h$ and the delay vector $\mathbf{l}_m$, which are utilized to estimate the multiuser fading channels. The third case is the BER of the system with estimated $\mathbf{R}_h$ and $\mathbf{l}_m$. The fourth case is the BER of the system that employs the LS-based method [11] to estimate the channel coefficients at pilot locations, where the LS-based algorithm only utilizes the first order statistics of the fading channel, and the results are labeled as "LS-based method". As can be seen from Fig. 2, when the receiver knows $\mathbf{R}_h$ and $\mathbf{l}_m$, our estimation algorithm has nearly the same BER performance as the ideally perfect channel estimation case. However, as expected, when the receiver has to estimate both $\mathbf{R}_h$ and $\mathbf{l}_m$, the proposed algorithm will have a little degradation, but the degradation is within an acceptable range. For example, it is about 0.8dB when the BER is at the level of 10^{-4}.

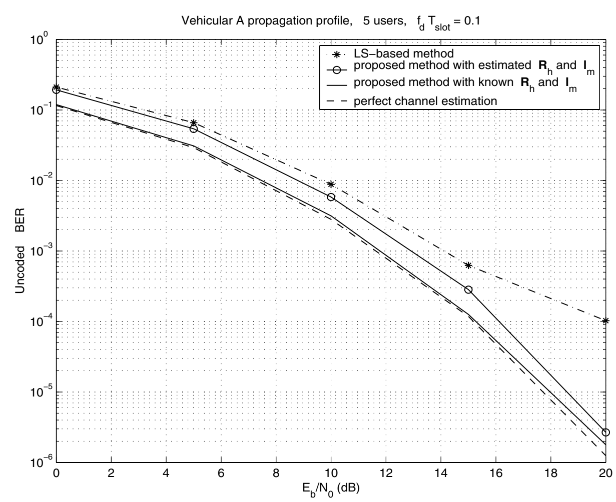

Fig. 2. BER performance comparison of the system which employs our multiuser channel estimation algorithm and the ideally perfect channel estimation.

Comparing the four curves above, we can see that the channel correlation matrix $\mathbf{R}_h$ plays a very important role in the performance of the estimation algorithm. If we do not take advantage from this correlation information , we will get BER performance penalty which can be significant compared to our proposed MMSE-based algorithm.

To further show our proposed algorithm's ability of estimating $\mathbf{l}_m$, we consider two cases that the maximum transmission delay factor D is set to 3 and 6. First, we assume that the delay vector $\mathbf{l}_m$ is known to the receiver, and the obtained BER curves are labeled "known $\mathbf{l}_m$" in Fig. 3. Second, when the vector $\mathbf{l}_m$ is estimated with our proposed iterative method, the obtained BER curves are labeled "estimated $\mathbf{l}_m$". It is noted that all the four curves in Fig. 3 are based on the estimated $\mathbf{R}_h$ by using our iterative algorithm. From Fig. 3, we have three observations. First, when the receiver has knowledge of $\mathbf{l}_m$, changing the maximum transmission delay range has no apparent effect on the system performance. Second, whereas for a system with $\mathbf{l}_m$ being estimated, a slight BER degradation will occur if D is increased. Third, the BER performance of a system with estimated $\mathbf{l}_m$ are close to that of a system with perfect information of $\mathbf{l}_m$. These results indicate that the proposed algorithm provides accurate estimation of $\mathbf{l}_m$ in a wide range of E_b/N_0.

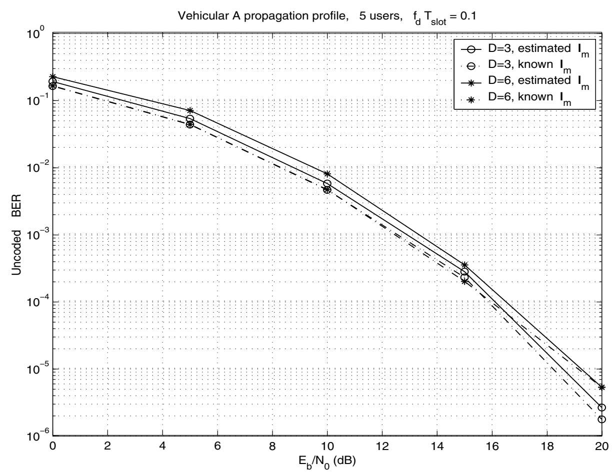

Fig. 3. BER comparison for the effect of the tap delay vector $\mathbf{l}_m$ on system performance.

So far, all the simulation results are focused on the Vehicular A propagation profile, which has discrete-time power delay profile. We would like to point out that our algorithm can be directly applied to channels which have continuous-time power delay profile. For example, we replace Vehicular A profile by an exponentially decaying profile $G_m^c(\tau) = A \cdot \exp\left(-\frac{\tau}{1\mu s}\right)$ with $0 \leq \tau \leq 1.5\mu s$. If we keep the rest of simulation configurations of Fig. 2 unchanged, then we get the corresponding BER comparison for $G_m^c(\tau)$ as shown in Fig. 4, which indicates that our algorithm is still very effective under continuous-time power delay profile fading environment. However, it should be pointed out that many existing channel estimation algorithms will fail under this fading condition.

VI. Conclusions

In this paper, a pilot assisted MMSE multiuser channel estimation algorithm was proposed for QS-CDMA systems undergoing a doubly selective channel fading. The algorithm is developed based on the only assumption that the base station knows the spreading codes and pilot symbols of all the mobile

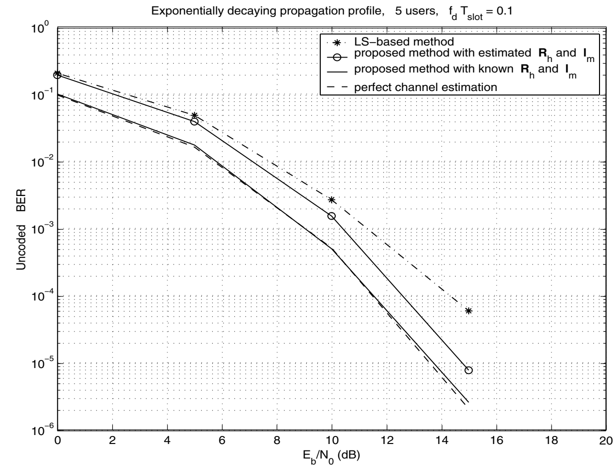

Fig. 4. BER performance comparison of the system with power delay profile being a continuous-time exponentially decaying function.

users. The proposed algorithm can be used to estimate fading channels which have either discrete-time or continuous-time power delay profiles. Simulation results show that the information of the channel tap correlations is critical to the performance of the multiuser channel estimation, and the channel taps at different delays may not be assumed uncorrelated for CDMA systems experiencing doubly selective fading.

Furthermore, when the channel tap correlation is known to the receiver, the BER performance of the proposed algorithm is nearly the same as that of the perfect channel estimation case; when the channel tap correlation is estimated from the received signals, the proposed algorithm's BER performance is close to that of the perfect channel estimation case.

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