# Multi-Rate MC-DS-CDMA with Multiuser Detections for Wireless Multimedia Communications

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*Abstract*-**In this paper, we study the multi-rate transmission for MC-DS-CDMA systems based on the concepts of multi-code (MC) access and variable-spreading-length (VSL) code access. The general system model is derived for multi-rate MC-DS-CDMA systems of either multi-rate access and multiuser detections (MUD) are proposed thereof. We analyze the characteristics of multi-rate MC-DS-CDMA signals and investigate the behaviors of MUDs. Compared studies and simulations among the proposed MUDs and access methods suggest VSL-code access with the proposed LMMSE detection to multi-rate MC-DS-CDMA systems, especially for transceiving high-rate users.**

## I. INTRODUCTION

In the future, multimedia communications will be the main stream of wireless communication systems and realizing effective multi-rate physical-layer transmission becomes a highly challenging research in the current development of high-speed wireless communications. Wideband and various data rate are the features of multimedia traffic, and meanwhile, it will suffer from more hostile fading channels. Recent years, some new transmission methods based on the combination of code-division-multiple-access (CDMA) and orthogonal-frequency-division-multiplexing (OFDM) are proposed [1][2][3]. These transmission methods retain the advantages from both CDMA and OFDM techniques, such as high and soft-limited user capacity and robustness to multi-path fading channels. Furthermore, it mitigates the difficulty of equalization for frequency-selective faded wideband CDMA signals and makes finer partition of system resource into time, frequency, and code domain, which contributes to efficient resource utilizations. MC-DS-CDMA system is one of the OFDM-CDMA alternatives [3] and is the most direct combining of OFDM and time-domain direct-sequence CDMA. Previous researches proposed and studied the multi-rate transmission on single-carrier CDMA systems in AWGN channels [4][5]; however, multi-rate transmission for multi-carrier systems is rarely studied. We apply the concept of multi-code (MC) access and variable-spreading-length (VSL) code access that are proposed for DS-CDMA [4] to the MC-DS-CDMA systems and built uniform, general, and systematic model for uplink applications. Based on the general model, we proposed multiuser detections (MUD) under the criterion of maximum-likelihood for benchmark studies, and two practical criterions of linear implementation complexity, decorrelating and minimum-mean-squared error (MMSE). Respective performance and characteristics of detections in either multi-rate access are analyzed and verified in this paper with comprehensive numerical simulations, and the compared results are provided. Multi-rate MC-DS-CDMA with multiuser detections exhibits distinct properties from DS-CDMA and multi-rate MC-CDMA systems [6] whose spectrum is spread in frequency domain. VSL-code access provides better performance than MC access in MC-DS-CDMA systems, especially for users of higher data rate.

## II. MULTI-RATE MC-DS-CDMA

We assume there is a basic data rate in the system and all data rates in the system fit an integer multiple $m$ of the basic rate, and assume the basic symbol rate= $1/T_s$ .

### A. *Multi-Code Access*

The data stream of a user with rate $m$ is first multiplexed into $m$ different streams with basic rate and each is treated as an individual (effective) user with individual spreading codes. Each stream is then serial-to-parallel converted into $P$ parallel sub-streams and then the sub-streams from the same effective user are spread by the same spreading codes with constant factor $F$. Combining all the corresponding parallel spread signals from other effective users, they are transmitted by $P$ orthogonal sub-carriers respectively. The system could adopt the strategy in [2] to expend the transmission diversity with a factor $L$. Thus, each sub-stream before spreading is copied into $L$ branches and then been spread and transmitted by different sub-carriers. The transmitted signal of the user $k$ is,

$$x_k(t)=\sum_{j=1}^{m}\sum_{p=1}^{P}A_k b_{jp}\sum_{f=1}^{F}c_{jf}\varphi(t-fT_c)\sum_{l=1}^{L}e^{j2\pi((p-1)L+l)\Delta ft}, \qquad (1)$$

$0 \le t \le PT_s$ , where $b_{jp}$ is the $p$th symbol, $c_{jf}$, $f$=1,2,...,$F$ is the assigned spreading codes of the $j$th effective user, and $\varphi(t)$ is the unit-rectangular function with duration $T_c$, where $T_c = {PT_s}/{F}$ , $\Delta f = 1/{T_c}$, and totally $PL$ sub-carriers.

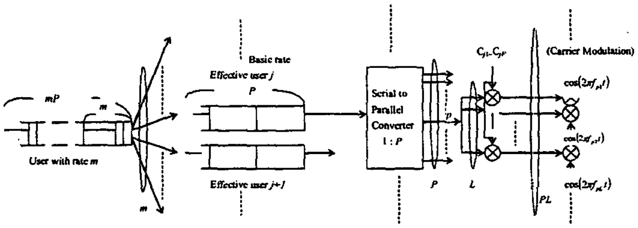

Fig. 1 Illustration for Multi-Code Access of MC-DS-CDMA

### B. *Variable-Spreading-Length Code Access*

Regardless any date rate, the data stream of any user is directly serial-to-parallel converted into $P$ sub-streams. In the afterward spreading stage, symbols at each sub-stream are

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spread in time domain as conventional DS-CDMA by spreading codes whose length is inversely proportional to the data rate. The transmission diversity could be expended by copying each sub-stream before the spreading stage into $L$ branches and data-streams from the same user are then spread by the same spreading codes but transmitted by different sub-carriers. Totally $PL$ orthogonal sub-carriers are used. The transmitted signal of the user $k$ with rate $m$ is:

$$x_k^m(t)=\sum_{p=1}^{Pm}\sum_{l=1}^{L}A_k^m b_{kp}^m \sum_{f}^{F/m} c_{kf}^m \varphi\left(t-fT_c-(p-1)\frac{PT_s}{m}\right)\sum_{l=1}^{L} e^{j(((p-1)\bmod P)L+l)\Delta f t},$$

$$0 \le t \le PT_s, \qquad (2)$$

where $b_{kp}^m$ is the $p$th symbol and $A_k^m$ is the transmitted amplitude respectively, $T_c = PT_s/F$ and $\Delta f = 1/T_c$. $c_{kf}^m \in \{\pm 1\}$ denotes the $f$th bit of the assigned spreading codes.

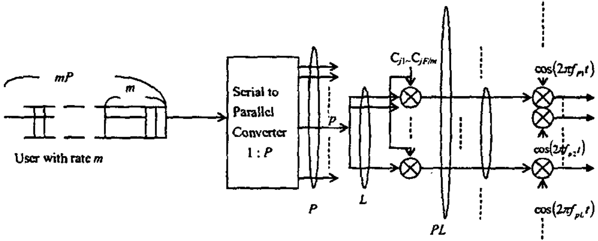

Fig. 2 Illustration for Variable-Spreading-Length Access of MC-DS-CDMA

## III. SIGNAL MODEL OF MULTI-RATE MC-DS-CDMA

We expect the wireless channels are frequency-selective fading with respect to the original symbol rate and whole bandwidth. However, we can set an appropriate number of sub-carriers such that the bandwidth of sub-channel is smaller than the coherence bandwidth to yield frequency-nonselective fading on each sub-carrier [3]. Furthermore, we assume sub-channels are mutually uncorrelated and slow Rayleigh fading [7]. To maintain slow fading, the number of sub-carriers is upper bounded by $F/(f_{D\max}T_s)$, where $f_{Dmax}$ is the maximum Doppler frequency.

The signal formulation is complicated in VSL-code access systems due to various symbol durations of multi-rate users. Hence, we alternatively decompose a user with rate $m$ in VSL-code access as $m$ effective users, which brings a more compact and systematic formulation. The decomposition, corresponding spreading codes, and spectrum distribution are illustrated in Fig. 3. Let $K_m$ denote the number of users with rate $m$, there are $K=\sum_{m=1}^{M} mK_m$ effective users as in MC access and $P$ symbols for each within the considered "one-shot" duration in a system containing $M$ data rates. Re-labeling effective users, the received signal in a multi-rate MC-DS-CDMA system, regardless of MC or VSL-code access, is

$$y(t)=\sum_{k=1}^{K}\sum_{p=1}^{P}A_k b_{kp}\sum_{f=1}^{F}c_{kf}\varphi(t-fT_c)\sum_{l=1}^{L}\alpha_{kpl}e^{j2\pi((p-1)L+l)\Delta f t}+n(t), \qquad (3)$$

$0 \le t \le PT_s$ where $b_{kp}$ is the $p$th symbol, $A_k$ is the amplitude, $\alpha_{kpl}$ is the channel response of the $[(p-1)L+l]$th sub-channel of the $k$th effective user with normalized expectation $E\left[|\alpha_{kpl}|^2\right]=1$, and $n(t)$ is AWGN with 2-sided PSD $N$o/2.

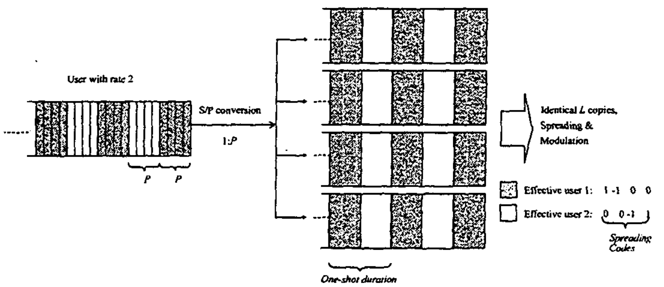

Fig. 3 Illustration of effective users in VSL-code access MC-DS-CDMA systems.
A user of twice the basic rate with spreading codes 1 -1 is for example; Serial-to-parallel ratio $P$= 4.

To detect the $p$th symbol of all effective users, we need only signals in the corresponding $L$ sub-carriers due to mutually orthogonal sub-carriers. We drop the sub-script $p$ for clarity, and these $L$ signals after down conversions are:

$$\begin{aligned} r_i(t) &= \sum_{k=1}^{K}\alpha_{kpi}A_k b_{kp}\sum_{j=1}^{F}c_{kj}\varphi(t-(j-1)T_c)+n_{pi} \\ &= \sum_{k=1}^{K}\alpha_{kpi}A_k b_{kp}s_k(t)+n_{pi} \end{aligned} \qquad (4)$$

where $s_k(t)\equiv\sum_{j=1}^{F}c_{kj}\varphi(t-(j-1)T_c)$ with $\int_0^{PT_s}s_k^2(t)dt=1$ and $n_{pl}=\int_{(i-1)T_c}^{T_c}n(t)\varphi(t)dt$ for $l$=1,2,…,$L$. It can be proved that $\{s_k(t)|k=1,2,\dots,K\}$ compose a complete basis of the signal space. Thus, for each $r_i(t), i=1,2,\dots,L$, we can derive the sufficient statistics, which is a $K\times 1$ vector:

$$\mathbf{y}_i=[y_{i1}y_{i2}\cdots y_{iK}]^T, \qquad (5)$$

where

$$y_{ik'} \equiv \int_0^{T_s} r_i(t)s_{k'}(t)dt=\sum_{k=1}^{K}\alpha_{ki}A_k b_k\rho_{kk'}+n_{ik'} \qquad (6)$$

and $\rho_{ij}\equiv\int s_i(t)s_j(t)dt$. The sufficient vector in each path can be represented as

$$\mathbf{y}_i=\mathbf{RA}\boldsymbol{\alpha}_i\mathbf{b}+\mathbf{n}_i, \qquad (7)$$

where $\mathbf{A}=diag(A_1A_2\cdots A_K)$ and $\boldsymbol{\alpha}_i=diag(\alpha_{1i}\alpha_{2i}\cdots\alpha_{Ki})$, which is a general and uniform MIMO model for both MC access and VSL-code access. The structure of correlation matrix $\mathbf{R}$ distinguishes VSL-code access from MC access. $\mathbf{R}$ contains more zero terms in VSL-code access system. Based on the signal model and sub-channel diversity $L$, we develop multiuser detections in multi-rate MC-DS-CDMA systems of either access.

## IV. MULTIUSER DETECTIONS

We consider first the jointly minimum-error-probability detection [8] based on ML criterion to provide the fundamental analysis of MUD behaviors as the benchmark. Attribute to the well-structured signal model in (7), it provides platform for linear MUD techniques as DS-CDMA systems [9][10] and diversity-combining decisions. All detections are performed simultaneously for one-shot symbols, that is, $mP$

symbol decisions for users of rate $m$ within detection period $PT_s$ in either access.

### A. Maximum-Likelihood Detection

By observing the signals received at $L$ sub-carriers, it forms the likelihood function $\Pr\left(r_1(t), r_2(t), \cdots, r_{L(t)} \middle| \mathbf{b}\right)$, $0 \le t \le PT_s$. Given all channel coefficients and due to orthogonal sub-carriers, the ML detection of $\mathbf{b}$ is made by

$$\hat{\mathbf{b}} = \arg \underset{\mathbf{b}}{max}\left\{\prod_{i=1}^{L} \Pr\left(r_i(t) \middle| \mathbf{b}\right)\right\} = \arg \underset{\mathbf{b}}{max}\left\{\sum_{i=1}^{L} log \Pr\left(r_i(t) \middle| \mathbf{b}\right)\right\}$$

$$= \arg \underset{\mathbf{b}}{min}\left\{\sum_{i=1}^{L} \int_0^{T_s} \left| r_i(t) - \sum_{k=1}^{K} \alpha_{kl} A_k b_k s_k(t) \right|^2 dt\right\}$$

$$= \arg \min_{\mathbf{b}} \sum_{i=1}^{L} \left\{\mathbf{b}^T \boldsymbol{\alpha}_i^H \mathbf{ARA}\boldsymbol{\alpha}_i \mathbf{b} - 2\,\mathrm{Re}\left[\mathbf{b}^T \boldsymbol{\alpha}_i^H \mathbf{Ay}_i\right]\right\}, \tag{8}$$

where $\mathbf{A} = diag(A_1 A_2 \cdots A_K)$ and $\boldsymbol{\alpha}_i = diag(\alpha_{1i}\alpha_{2i} \cdots \alpha_{Ki})$.
In cases of using orthogonal spreading codes, equation (8) can be reduced to

$$\hat{\mathbf{b}} = \arg \max_{\mathbf{b}} \sum_{i=1}^{L} \mathrm{Re}\left[\mathbf{b}^T \boldsymbol{\alpha}_i^H \mathbf{Ay}_i\right] \tag{9}$$

Except for the equivalent channel coefficients $\{\alpha_{kl} A_k \mid k = 1,2,\ldots,K; l = 1,2,\ldots,L\}$, only the matched-filter outputs $\{\mathbf{y}_i \mid i = 1,2,\ldots,L\}$ compose sufficient statistics. Enough sub-carriers and orthogonality transform frequency-selective fading into uncorrelated diversity.

### B. Decorrelating Detection

The symbol of the desired user can be extracted by forcing the components from other users to zeros. In fact, we can construct a more general MIMO model, whose input $\mathbf{b}$ and output vector $\left[\mathbf{y}_1^H \mathbf{y}_2^H \cdots \mathbf{y}_L^H\right]^H$. It introduces the problem of solving a set of $LK$ linear equations. However, this may cause tremendous complexity on computing the inverse of large size matrix, especially when the number of sub-carriers is large to combat server multi-path channels. We alternatively resort to the equivalent MIMO model $\mathbf{y}_i = \mathbf{RA}\boldsymbol{\alpha}_i \mathbf{b} + \mathbf{n}_i$ carrier by carrier, and weighted-combine the results. Given the channel coefficients and spreading codes of all effective users, let $\mathbf{M}_i = \mathbf{RA}\boldsymbol{\alpha}_i$, a $K \times K$ matrix, and assumed full rank. The estimate of $\mathbf{b}$ at the $i$th homologous sub-carrier is

$$\tilde{\mathbf{b}}_i = \left(\mathbf{RA}\boldsymbol{\alpha}_i\right)^{-1} \mathbf{y}_i \tag{10}$$

and the decision of the $k$th effective user by combining the results from the $L$ homologous sub-carriers is:

$$\hat{b}_k = sign\left(\sum_{i=1}^{L} |\alpha_{ki}| \tilde{b}_{ki}\right), \tag{11}$$

which is named Magnitude-Proportional combining (MPC).

### C. Linear MMSE Detection

Similarly, we perform LMMSE detection carrier by carrier to mitigate complexity and make final decisions by weighted combing. For $i$th homologous sub-carrier, denote the linear detector for $\mathbf{b}$ as a $K \times K$ matrix $\mathbf{W}_i$. Let the vector of decision variables $\tilde{\mathbf{b}}_i = \mathbf{W}_i \mathbf{y}_i$, $l$=1,2,...,$L$. To acquire $\mathbf{W}_i$ that minimizes the mean-squared error $E\left[\left|\mathbf{W}_i^H \mathbf{y}_i - \mathbf{b}\right|^2\right]$, the principle of orthogonality implies

$$E\left[\left(\mathbf{b} - \mathbf{W}_i \mathbf{y}_i\right) \mathbf{y}_i^H\right] = 0 \tag{12}$$

and yields the MMSE solution:

$$\mathbf{W}_l = \boldsymbol{\alpha}_i^H \mathbf{AR}\left(\mathbf{RA}\boldsymbol{\alpha}_i \boldsymbol{\alpha}_i^H \mathbf{AR} + No\mathbf{I}\right)^{-1} \tag{13}$$

Symbol decision for $k$th effective user is made by MPC the results of $L$ homologous sub-carriers:

$$\hat{b}_k = sign\left(\sum_{i=1}^{L} |\alpha_{ki}| \tilde{\mathbf{b}}_{ik}\right), \tag{14}$$

where $\tilde{\mathbf{b}}_{lk}$ denotes the $k$th element of $\tilde{\mathbf{b}}_l$.
As well as in DS-CDMA systems, the LMMSE detection approaches the decorrelating detection asymptotically at high signal-to-noise power ratio (SNR) situation,

$$\mathbf{W}_l \approx a_i^H \mathbf{AR}\left(\mathbf{RA}\, a_i a_i^H \mathbf{AR}\right)^{-1} = \left(\mathbf{RA}\, a_l^H\right)^{-1} \tag{15}$$

However, LMMSE detection alleviates the probable noise enhancement problem of decorrelating detection in case channels cause the equivalent channel matrix near singular.

## V. PERFORMANCE ANALYSIS

We use the maximum-likelihood detection to derive the minimum error probabilities of multi-rate MC-DS-CDMA systems. The closed form of error probability in ML detection is generally difficult to derive and usually the bounds were formulated instead. We apply the method of error vector [8]. The error vector is defined as:

$$\boldsymbol{\varepsilon} = \left[\varepsilon_1 \varepsilon_2 \cdots \varepsilon_K\right]^T \equiv \tfrac{1}{2}\left(\mathbf{b} - \hat{\mathbf{b}}\right) \text{ where } \varepsilon_k \in \{0, \pm 1\}. \tag{16}$$

It represents all error decisions that may happen. Equation (8) follows the decision metric function

$$\Omega\left(\mathbf{b} \middle| \{\boldsymbol{\alpha}_l | l = 1,2,..,L\}\right) \equiv \mathrm{Re}\left\{\sum_{i=1}^{L} \mathbf{b}^H \boldsymbol{\alpha}_i^H \mathbf{Ay}_i\right\} - \tfrac{1}{2}\sum_{i=1}^{L} \left|\mathbf{A}\boldsymbol{\alpha}_i \mathbf{b}\right|^2 \tag{17}$$

Denote $\overline{\boldsymbol{\alpha}}_L = \{\boldsymbol{\alpha}_l | l = 1,2,..,L\}$ and assume $\mathbf{b}$ is transmitted, the error probability of the $k$th effective user under the channel realizations $\overline{\boldsymbol{\alpha}}_L$ is upper bounded by

$$P_k(\overline{\boldsymbol{\alpha}}_L) \le \sum_{\boldsymbol{\varepsilon} \in E_k} \Pr\left\{\Omega\left(\mathbf{b} - 2\boldsymbol{\varepsilon} \middle| \overline{\boldsymbol{\alpha}}_L\right) is \text{ max}, \boldsymbol{\varepsilon}\ is\ admissable\right\}^{1}$$

$$\le \sum_{\boldsymbol{\varepsilon} \in E_k} \Pr\left\{\boldsymbol{\varepsilon}\ is\ admissable\right\} \Pr\left\{\Omega(\mathbf{b} - 2\boldsymbol{\varepsilon}) \ge \Omega(\mathbf{b}) \middle| \overline{\boldsymbol{\alpha}}_L\right\} \tag{18}$$

which results from the union bound of all possible joint error decisions. In (18), it uses the fact that whether an error vector is admissible depends only on the transmitted symbols [8] and with probability $2^{-w(\boldsymbol{\varepsilon})}$ for equal-likely transmitted bits, where $w(\boldsymbol{\varepsilon})$ denotes the Hamming weight of $\boldsymbol{\varepsilon}$. Besides, the difference of metrics under any error event $\boldsymbol{\varepsilon}$ given the channels $\overline{\boldsymbol{\alpha}}_L$ is:

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[1] $\boldsymbol{\varepsilon}$ is said admissible with a transmitted $\mathbf{b} \in \{\pm 1\}^K$ if $\varepsilon_i = b_i\ or\ 0, \forall i$. [8]

$$\Omega(\mathbf{b}-2\boldsymbol{\varepsilon})-\Omega(\mathbf{b})=\sum_{i=1}^{L}\left[-2\,\mathrm{Re}\left(\boldsymbol{\varepsilon}^{H}\boldsymbol{\alpha}_{i}^{H}\mathbf{A}\mathbf{n}\right)-2\boldsymbol{\varepsilon}^{H}\boldsymbol{\alpha}_{i}^{H}\mathbf{ARA}\boldsymbol{\alpha}_{i}\boldsymbol{\varepsilon}\right] \tag{19}$$

Decompose $\sum_{l=1}^{L}\boldsymbol{\varepsilon}^{H}\boldsymbol{\alpha}_{i}^{H}\mathbf{A}^{H}\mathbf{R}\boldsymbol{\alpha}_{l}\boldsymbol{\varepsilon}=\left\|\mathbf{M}_{L}\left(\boldsymbol{\varepsilon}|\overline{\boldsymbol{\alpha}}_{L}\right)_{(LK\times 1)}\right\|^{2}$ , and Gaussian distribution of (19) yields

$$\Pr\left\{\Omega(\mathbf{b}-2\boldsymbol{\varepsilon})-\Omega(\mathbf{b})\geq 0|\overline{\boldsymbol{\alpha}}_{L}\right\}=Q\left(\sqrt{2}\left\|\mathbf{M}_{L}\left(\boldsymbol{\varepsilon}|\overline{\boldsymbol{\alpha}}_{L}\right)\right\|/\sqrt{No}\right) \tag{20}$$

The expected error probability over channel realizations,

$$P_{k}\leq\sum_{\boldsymbol{\varepsilon}\in E_{k}}2^{-w(\boldsymbol{\varepsilon})}\int_{\overline{\boldsymbol{\alpha}}_{L}}Q\left(\sqrt{2}\left\|\mathbf{M}_{L}\left(\boldsymbol{\varepsilon}|\overline{\boldsymbol{\alpha}}_{L}\right)\right\|/\sqrt{No}\right)p\left(\overline{\boldsymbol{\alpha}}_{L}\right)d\overline{\boldsymbol{\alpha}}_{L}, \tag{21}$$

where $p\left(\overline{\boldsymbol{\alpha}}_{L}\right)$ denotes the probability density function (pdf) of $\overline{\boldsymbol{\alpha}}_{L}$. Utilizing the expectation identity for $Q(.)$ function of Gaussian quadratic form, the error probability upper bound of the *k*th effective user is:

$$P_{k}\leq\sum_{\varepsilon\in E_{k}}2^{-w(\varepsilon)}\sum_{i=1}^{Lw(\boldsymbol{\varepsilon})}\frac{\eta_{i}}{2}\left(1-1\Big/\sqrt{1+N_{0}/\lambda_{i}}\right), \tag{22}$$

where $\lambda_{i}$ is the *i*th distinct nonzero eigenvalue of $E\left[\mathbf{M}_{L}\mathbf{M}_{L}^{H}\right]$, and $\eta_{i}\equiv\prod_{i=1,i\neq j}^{Lw(\varepsilon)}\frac{\lambda_{i}}{\lambda_{i}-\lambda_{j}}$ [11]. The concept of indecomposable error vector set as defined in [8][12] helps to tighten the bound in (22). On the other hand, detecting one effective user with the information of others' transmitted symbols yields the lower bound of error probability of the *k*th effective user:

$$P_{k}\geq\left[\tfrac{1}{2}\left(1-\frac{1}{\sqrt{1+No/\zeta}}\right)\right]^{L}\sum_{n=0}^{L-1}\binom{L-1+n}{n}\left[\tfrac{1}{2}\left(1+\frac{1}{\sqrt{1+No/\zeta}}\right)\right]^{n} \tag{23}$$

where $\zeta\equiv E_{b}/\mathrm{E}\left(|\alpha_{l}|^{2}\right)$ assumed identical for each sub-carrier. The above formulations are derived on the basis of effective users, and noted that the patterns of effective users are different in MC and VSL-code access. In fact, the derived expression is general for all CDMA systems receiving with uncorrelated diversity.

## VI. NUMERICAL SIMULATIONS

For simplicity and without loss of generality, we consider the case of two data rates and the higher rate is twice the lower. Assume there are respectively two users of each rate, which results in six effective users. The transmitted symbols of each user are uniformly binary-distributed of ±1 and the signal of each original user passes an individual set of slow Rayleigh fading sub-channels, generated by complex Gaussain distribution with uncorrelated real and imaginary parts and $E[|\alpha_{kf}|^{2}]=1$ for all *k* and *f*.

### *A. BER of MUDs in Both Access Methods:*

(1) We suppose equal cross-correlation among spreading codes to investigate the fundamental characteristics of MUDs. Assume the number of homologous paths *L*=4 and the cross-correlation value=0.1. The consumed energy $E_b$ for transmitting an original symbol of any rate is assumed equal Fig. 4 (a)(b)(c) show the performance results. The results show that transmitting high rate users by VSL-code access gets significantly better performance than by MC access. The BER of low-rate users in VSL-code access is higher than high-rate users but roughly the same as users of any rate in MC access. The pattern of cross-correlation matrix dominates the detection error probability of multi-rate MC-DS-CDMA systems and relative performance between the two access methods. In Fig. 4 (d), we take MC access as instance to compare the relative performance among MUDs. Also in this figure is the BER of applying direct-average-sum (DAS) to combine the estimate results of all homologous paths for comparison. This figure shows the benchmark BER of ML detection and the proposed LMMSE detection with MPC exhibits approaching performance. Decorrelating detection is still persecuted by noise enhancement problem and thus performs slightly worse than LMMSE detection, even though they will merge together asymptotically.

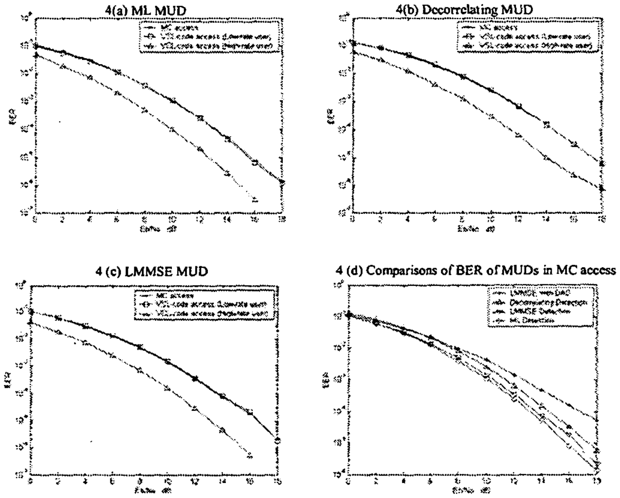

Fig. 4 BER of MUDs in Multi-rate MC-DS-CDMA systems. 2 basic rate users and 2 double rate users assigning spreading codes with cross-correlation–0.1.

(2) Consider the special case of using orthogonal spreading codes. Also assume 4 homologous paths for each symbol, and Hadamard Walsh codes of length *F*=16 for each effective user in MC access, and *F*=16 and *F*=8 for low-rate and high-rate users respectively in VSL-code access. Given equal energy per symbol $E_b$, the BERs in both access methods are shown in Fig. 5 (a) (b) (c). We can find that the BERs of MUDs for multi-rate MC-DS-CDMA in MC access and VSL-code access are roughly the same, although in VSL-code access it shows a little better. Compared with the previous scenario, less involved interference and higher power of VSL-code access signals do not get significant advantages over MC access, which is due to the orthogonality of spreading codes can be preserved in MC-DS-CDMA systems, unlike the distinct results in multi-rate Multi-Carrier-CDMA systems [6]. Spreading codes with low cross-correlation is critical to

MC access to transmit high-rate data. The BERs of MUDs in MC access are plotted in Fig. 5 (d) for comparison.

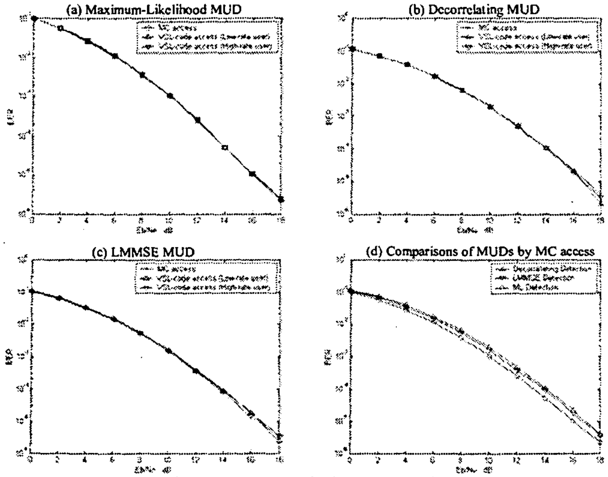

Fig. 5 BER of multiuser Detections in MC-DS-CDMA systems with Hadamard Walsh

### B. *BERs vs. Channel diversity L:*

Transmit identical symbols by several channels provide receiving diversity in fading channels. We take MC access for instance to show the effect of diversity gain, plotted in Fig. 6. The detection performance is improved with increased $L$, and the performance gap between LMMSE and Decorrelating detections increases. However, there is a tradeoff that the maximum length of spreading codes $F$ is inversely proportional to the diversity $L$ given a fixed spectrum in MC-DS-CDMA system. Increasing $L$ reduces system capacity and the maximum affordable data rate.

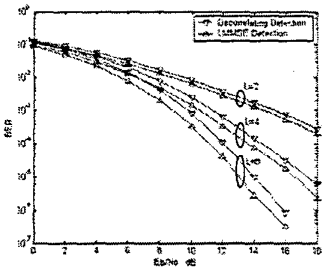

Fig. 6 BER v.s. Channel Diversity $L$

### C. *Performance at different rate combination:*

We simulate the scenario of two basic-rate users and one high-rate user with rate 4 in VSL-code access. There are still six effective users as previous but the rate ratio of the high-rate user over the low-rate users becomes 4. The cross-correlation among spreading codes is 0.1. The results are illustrated in Fig. 7, which shows the advantage of VSL-code access in transmitting high-rate users. Such predominance of VSL-code access is reduced with the increase of orthogonality among spreading codes.

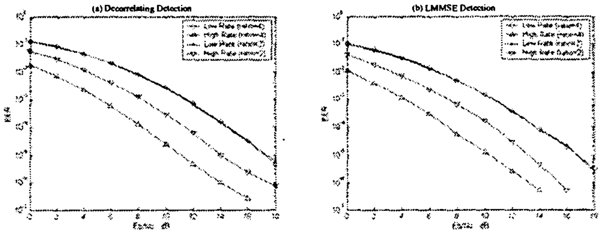

Fig. 7 BER of MUDs in multi-rate MC-DS-CDMA systems at rate ratio 1:4 and 1:2

## IV. CONCLUSIONS

In this paper, we studied the multi-rate transmission and developed effective multiuser detections for MC-DS-CDMA systems. The characteristics of signals with multi-rate access and the properties of MUDs are analyzed and the comparisons among access methods, MUD strategies, structures of spreading codes, and diversity gains are comprehended. The LMMSE detection with MPC is effective in practice and VSL-code access is suggested for high-data-rate users, although sacrifices some module regularity in system implementation. If adopting MC access, good design of spreading codes is critical to detection performance and essential to the inherent demand of larger code set. The future and extended work further studies the resource allocation for wireless multimedia communications.

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