# Frequency-Domain Block Signal Detection of Multi-Code DS-CDMA Signals

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***Abstract*—In this paper, we propose a block signal detection scheme, which combines frequency-domain equalization and signal detection scheme developed for the multiple-input multiple-output (MIMO) multiplexing, for the reception of the multi-code direct sequence code division multiple access (DS-CDMA) signals. The proposed signal detection scheme is described first. Then, we evaluate, by computer simulation, the achievable bit error rate (BER) performance of multi-code DS-CDMA using the proposed frequency-domain block signal detection and discuss the impacts of spreading factor and code multiplexing order on the BER performance.**

***Keywords-component; DS-CDMA, MMSE, V-BLAST, QRM-MLD***

## I. INTRODUCTION

In a severe frequency-selective fading channel, the bit error rate (BER) performance significantly degrades due to inter-symbol interference (ISI) when single carrier (SC) transmission without equalization technique is used [1]. Direct sequence code division multiple access (DS-CDMA) using coherent rake combining is adopted to obtain the path-diversity gain in the third generation mobile communication systems for data transmissions of up to a few Mbps [2]. However, for data transmissions of higher than a few 100 Mbps, the BER performance of DS-CDMA with rake combining degrades severely [3].

One-tap frequency-domain equalization (FDE) based on the minimum mean square error criterion (MMSE) can replace rake combining to significantly improve the BER performance of broadband multi-code DS-CDMA [3-5]. However the BER performance of multi-code DS-CDMA using simple one-tap MMSE-FDE degrades as the code multiplexing order increases. This is because of the presence of residual inter-chip interference (ICI) after FDE resulting from the strong frequency-selectivity of the channel [6]. A frequency-domain ICI cancellation technique combined with MMSE-FDE was proposed in [6]. However, the achievable BER performance is still a few dB away from the theoretical lower bound.

In this paper, we take another approach to improve the BER performance in a strong frequency-selective channel. The frequency-domain received SC signal can be expressed using the matrix representation similar to the multiple-input multiple-output (MIMO) multiplexing. This implies that signal detection schemes developed for MIMO multiplexing, other than simple one-tap MMSE-FDE, can be applied to the SC transmissions. Recently, we proposed a new signal detection scheme, which combines FDE with MIMO signal detection, for the reception of SC signals (we call this frequency-domain block signal detection) [7]. Among the well-known MIMO signal detection schemes, the MMSE detection [1], the Vertical-Bell Laboratories layered space-time architecture (V-BLAST) detection [8] and the maximum likelihood detection (MLD) employing QR decomposition and M-algorithm (QRM-MLD) [9] can be used.

In this paper, we extend the proposed frequency-domain block signal detection to the reception of multi-code DS-CDMA signals. The frequency-domain received multi-code DS-CDMA signal can be also expressed similar to the MIMO multiplexing by regarding a concatenation of DS-CDMA code spreading & multiplexing at the transmitter, propagation channel, and fast Fourier transform (FFT) at the receiver as an equivalent channel. In the multi-code DS-CDMA, the signal-to-interference plus noise power ratio (SINR) of each data symbol is different since a different orthogonal spreading code is assigned. Therefore, when using V-BLAST or QRM-MLD, the detection ordering is introduced based on the SINR. The achievable BER performance of multi-code DS-CDMA transmissions is evaluated by computer simulation.

The remainder of this paper is organized as follows. Sect. II presents the multi-code DS-CDMA signal representation. In Sect. III, the principle of the proposed frequency-domain block signal detection is described. In Sect. IV, we evaluate, by computer simulation, the achievable BER performance of multi-code DS-CDMA using the proposed frequency-domain block signal detection and discuss the impacts of spreading factor and code multiplexing order on the BER performance. Sect. V offers the conclusion.

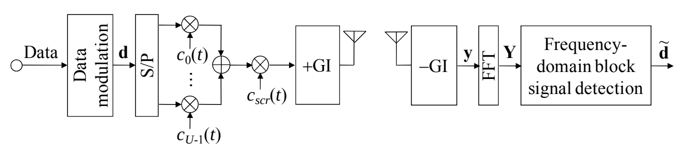



Figure 1. Multi-code DS-CDMA transmission system model.

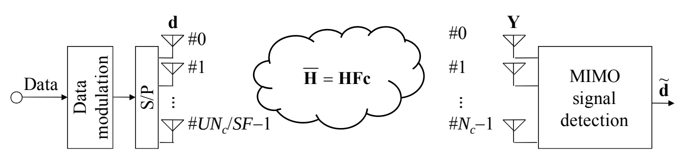



Figure 2. Equivalent system model.

## II. SIGNAL REPRESENTATION

The multi-code DS-CDMA transmission model is illustrated in Fig. 1. A block transmission of $U\times N_c/SF$ symbols is considered. At the transmitter, the data symbol sequence of $U\times N_c/SF$ symbols to be transmitted is serial/parallel (S/P) converted into $U$ parallel streams, where $N_c$ is the size of fast Fourier transform (FFT). The $u$th stream $\{d_u(n); n=0\sim N_c/SF-1\}$, $u=0\sim U-1$, is spread by an orthogonal spreading code $\{c_u(t); t=0\sim SF-1\}$ with the spreading factor $SF$. The resultant $U$ chip streams are added and multiplied by a common scramble sequence $\{c_{scr}(t); t=0\sim N_c-1\}$. Finally, the $N_g$-chip cyclic prefix (CP) is inserted into the guard interval (GI) and a multi-code DS-CDMA chip-block of $N_c+N_g$ chips is transmitted.

We assume a chip-spaced frequency-selective fading channel composed of $L$ distinct propagation paths. The channel impulse response $h(\tau)$ is given by

$$h(\tau)=\sum_{l=0}^{L-1}h_l\delta(\tau-\tau_l)\,, \tag{1}$$

where $h_l$ and $\tau_l$ are respectively the complex-valued path gain with $E[\sum_{l=0}^{L-1}|h_l|^2]=1$ and the time delay of the $l$th path. The GI-removed received signal block $\mathbf{y}=[y(0), ..., y(N_c-1)]^T$ can be expressed using the vector form as

$$\mathbf{y}=\sqrt{2E_c/T_c}\,\mathbf{hcd}+\mathbf{n}\,, \tag{2}$$

where $E_c$ and $T_c$ are respectively the chip energy and the chip duration, $\mathbf{h}$ is an $N_c\times N_c$ channel impulse response matrix, $\mathbf{c}$ is an $N_c\times N_c(U/SF)$ spreading matrix, $\mathbf{d}=[d_0(0), ..., d_{U-1}(0), ..., d_0(N_c/SF-1), ..., d_{U-1}(N_c/SF-1)]^T$ is the transmitted data symbol vector, and $\mathbf{n}=[n(0), ..., n(N_c-1)]^T$ is the noise vector. The $t$-th element, $n(t)$, of $\mathbf{n}$ is the zero-mean additive white Gaussian noise (AWGN) having the variance $2N_0/T_c$ with $N_0$ being the one-sided noise power spectrum density. $\mathbf{h}$ and $\mathbf{c}$ are given as

$$\mathbf{h}=\begin{bmatrix} h_0 & & & & & h_{L-1} & & \\ \vdots & h_0 & & & & & \ddots & \\ & \vdots & h_0 & \mathbf{0} & & & & h_{L-1} \\ h_{L-1} & & \vdots & \ddots & & & & \\ & h_{L-1} & & & & h_0 & & \\ & & h_{L-1} & & & \vdots & \ddots & \\ \mathbf{0} & & & \ddots & & & & h_0 \end{bmatrix} \tag{3}$$

$$\begin{cases} \mathbf{c}=\begin{bmatrix} \mathbf{c}^{(0)} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{c}^{(N_c/SF-1)} \end{bmatrix} \\ \mathbf{c}^{(n)}=\begin{bmatrix} c_0(0)c_{scr}(nSF) & \cdots & c_{U-1}(0)c_{scr}(nSF) \\ \vdots & \ddots & \vdots \\ c_0(SF-1) & \cdots & c_{U-1}(SF-1) \\ \times c_{scr}((n+1)SF-1) & & \times c_{scr}((n+1)SF-1) \end{bmatrix} \end{cases}. \tag{4}$$

At the receiver, $N_c$-point FFT is applied to transform the received signal block into the frequency-domain signal vector $\mathbf{Y}=[Y(0), \ldots, Y(N_c-1)]^T$. $\mathbf{Y}$ is expressed as

$$\mathbf{Y}=\mathbf{Fy}=\sqrt{2E_c/T_c}\,\mathbf{Fhcd}+\mathbf{Fn}\,, \tag{5}$$

where $\mathbf{F}$ is the FFT matrix of size $N_c\times N_c$ given by

$$\mathbf{F}=\frac{1}{\sqrt{N_c}}\begin{bmatrix} e^{-j2\pi\frac{0\times 0}{N_c}} & e^{-j2\pi\frac{0\times 1}{N_c}} & \cdots & e^{-j2\pi\frac{0\times(N_c-1)}{N_c}} \\ e^{-j2\pi\frac{1\times 0}{N_c}} & e^{-j2\pi\frac{1\times 1}{N_c}} & \cdots & e^{-j2\pi\frac{1\times(N_c-1)}{N_c}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j2\pi\frac{(N_c-1)\times 0}{N_c}} & e^{-j2\pi\frac{(N_c-1)\times 1}{N_c}} & \cdots & e^{-j2\pi\frac{(N_c-1)\times(N_c-1)}{N_c}} \end{bmatrix}. \tag{6}$$

Due to the circulant property of $\mathbf{h}$ [10], we have

$$\mathbf{FhF}^H=diag[H(0),\ldots,H(N_c-1)]\equiv\mathbf{H}\,, \tag{7}$$

where $H(k)=\sum_{l=0}^{L-1}h_l\exp(-j2\pi k\tau_l/N_c)$, $k=0\sim N_c-1$, and $(.)^H$ is the Hermitian transpose operation. Using Eq. (7), Eq. (5) can be rewritten as

$$\mathbf{R}=\sqrt{2E_c/T_c}\,\mathbf{HFcd}+\mathbf{N}=\sqrt{2E_c/T_c}\,\overline{\mathbf{H}}\mathbf{d}+\mathbf{N}\,, \tag{8}$$

where $\overline{\mathbf{H}}=\mathbf{HFc}$ and $\mathbf{N}=[N(0), ..., N(N_c-1)]^T$ are respectively the equivalent channel matrix and the frequency-domain noise vector.

From Eq. (8), it can be understood that the frequency-domain received signal can be treated as a received signal in MIMO multiplexing using $N_c(U/SF)$ transmit antennas and $N_c$ receive antennas whose channel matrix is given by $\overline{\mathbf{H}}$ (see Fig.2). According to this understanding, a new frequency-domain block signal detection scheme, which combines equalization and MIMO signal detection, can be developed for the reception of the multi-code DS-CDMA signals.

## III. Frequency-domain Block Signal Detection

Based on the fact that the frequency-domain received signal in multi-code DS-CDMA transmission has the same signal representation as an $N_c(U/SF)\times N_c$ MIMO multiplexing, we propose a new signal detection, called frequency-domain block signal detection. The frequency-domain block signal detection incorporates the signal detection scheme developed for the MIMO multiplexing into FDE. Among the well-known MIMO signal detection schemes, MMSE detection [1], the V-BLAST detection [8] and the QRM-MLD [9] can be used.

### A. MMSE detection

The MMSE detection is carried out using the weight matrix $\mathbf{W}$ and the decision variable vector $\tilde{\mathbf{d}}=[\tilde{d}(0),\ldots,\tilde{d}(m),\ldots,\tilde{d}_0(UN_c/SF-1)]^T$ is given by $\tilde{\mathbf{d}}=\mathbf{WY}$, where $\tilde{d}(m)$ is the decision variable associated with $d(m)=d_u(n)$, $m=u(N_c/SF)+n$, $u=0\sim U-1$, $n=0\sim N_c/SF-1$. The MMSE weight matrix $\mathbf{W}$ is derived as

$$\mathbf{W}=\overline{\mathbf{H}}^H\left[\overline{\mathbf{H}}\overline{\mathbf{H}}^H+(E_c/N_0)^{-1}\mathbf{I}_{N_c}\right]^{-1}, \tag{9}$$

where $\mathbf{I}_N$ is an $N\times N$ identity matrix.

### B. Iterative V-BLAST Detection

V-BLAST is composed of i) ordering, ii) interference cancellation, and iii) symbol detection. In the case of SC transmission, since the SINR is the same for all symbols, no ordering is necessary. On the other hand, in the case of multi-code DS-CDMA transmission, the SINR of each data symbol is different since a different orthogonal spreading code is assigned and the different interference is received from other symbols. The SINR of each symbol can be calculated using the equivalent channel matrix and the MMSE weight matrix.

At the initial iteration stage ($i$=0), the transmitted symbol, which has the highest SINR among undetected symbols is detected by performing MMSE detection [11]. The replica of the symbol, which has been just detected, is generated and is subtracted from the frequency-domain received signal. A new MMSE weight matrix for the undetected symbols is computed again and one of these symbols is detected. The $n$th round of above interference cancellation, ordering and symbol detection is called the $n$th layer and is repeated until all of the transmitted symbols are detected. However, the V-BLAST detection cannot suppress the ICI sufficiently, in particular for those symbols which have been detected earlier. To further improve the BER performance, iterative detection can be applied [12]. After all of transmitted symbols are detected, the V-BLAST detection is carried out again. This is repeated a sufficient number of times.

Below, without loss of generality, the transmitted symbols having the highest SINR is assumed to be the 0th symbol, followed by the 1st, 2nd,…,($N_c(U/SF)-1$)th symbols. In what follows, the symbol detection at the $n$th layer ($n$=0~ $N_c(U/SF)-1$) in the $i$th iteration stage is presented (assuming that the symbols with $n'$=0~$n-1$ have been detected in the present iteration stage).

#### 1) Ordering

First, ordering based on the SINR is performed to select the symbol, which has the highest SINR among the undetected symbols. The SINR $\gamma_m$ of the $m$th symbol ($m=n\sim N_c(U/SF)-1$) at the $i$th iteration stage can be obtained from

$$\gamma_m=\frac{(E_c/N_0)\left|\mathbf{W}_m^{(i,n)}\overline{\mathbf{H}}_m\right|^2}{\left\|\mathbf{W}_m^{(i,n)}\right\|^2+(E_c/N_0)\sum_{\substack{n'=n\\ \neq m}}^{UN_c/SF-1}\left|\mathbf{W}_m^{(i,n)}\overline{\mathbf{H}}_{n'}\right|^2},\tag{10}$$

where $\overline{\mathbf{H}}_n$ is the $n$th column vector of $\overline{\mathbf{H}}$. $\mathbf{W}_m^{(i,n)}$ is an $1\times N_c$ MMSE weight vector in the $n$th layer of the $i$th iteration stage to detect the $m$th symbol (the computation of MMSE weight will be explained later). Here, since the transmitted symbols having the highest SINR is assumed to be the 0th symbol, followed by the 1st, 2nd,…,($N_c(U/SF)-1$)th symbols, the $n$th symbol is detected in the $n$th layer.

#### 2) Interference cancellation

The frequency-domain received signal vector $\widetilde{\mathbf{Y}}^{(i,n)}$ at the $n$th layer in the $i$th iteration stage is given by

$$\widetilde{\mathbf{Y}}^{(i,n)}=\mathbf{Y}-\sqrt{2E_c/T_c}\,\overline{\mathbf{H}}\mathbf{s}^{(i,n)},\tag{11}$$

where $\mathbf{s}^{(i,n)}$ is the symbol replica vector, given by

$$\mathbf{s}^{(i,n)}=[s^{(i)}(0),\ldots,s^{(i)}(n-1),0,s^{(i-1)}(n+1),\ldots,s^{(i-1)}(UN_c/SF-1)]^T.\tag{12}$$

In the above, $\{\hat{s}^{(i)}(n');\, n'=0\sim n-1\}$ are generated using the decision results of the current iteration stage. On the other hand, $\{\hat{s}^{(i)}(n');\, n'=n+1\sim UN_c/SF-1\}$ are generated using the decision results of the ($i-1$)th iteration stage. We consider two types of iterative V-BLAST detection. The first (called the hard decision iterative V-BLAST in this paper) uses the hard symbol replica which is obtained from the hard decision result. The second (called the soft decision iterative V-BLAST in this paper) uses the soft symbol replica which is generated based on the log-likelihood ratio (LLR) [7].

#### 3) symbol detection

After interference cancellation, MMSE detection on the $n$th symbol is performed by multiplying $\widetilde{\mathbf{Y}}^{(i,n)}$ by an $1\times N_c$ MMSE weight vector $\mathbf{W}_n^{(i,n)}$ as $\widetilde{d}^{(i)}(n)=\mathbf{W}_n^{(i,n)}\widetilde{\mathbf{Y}}^{(i,n)}$. The MMSE weight vector $\mathbf{W}_n^{(i,n)}$ is given by [7]

$$\mathbf{W}_n^{(i,n)}=\begin{cases}\overline{\mathbf{H}}_n^H\left[\widetilde{\mathbf{H}}^{(i,n)}\widetilde{\mathbf{H}}^{(i,n)H}+\left(E_c/N_0\right)^{-1}\mathbf{I}_{N_c}\right]^{-1}\\ \quad\text{for hard decision iterative V-BLAST}\\ \overline{\mathbf{H}}_n^H\left[\overline{\mathbf{H}}\boldsymbol{\rho}^{(i,n)}\overline{\mathbf{H}}^H+\left(E_c/N_0\right)^{-1}\mathbf{I}_{N_c}\right]^{-1}\\ \quad\text{for soft decision iterative V-BLAST}\end{cases},\tag{13}$$

where

$$\widetilde{\mathbf{H}}^{(i,n)}=\begin{cases}[\overline{\mathbf{H}}_n,\overline{\mathbf{H}}_{n+1},\ldots,\overline{\mathbf{H}}_{UN_c/SF-1}] & \text{for } i=0\\ \overline{\mathbf{H}}_n & \text{for } i>0\end{cases}\tag{14}$$

and

$$\boldsymbol{\rho}^{(i,n)}=diag[\rho_0^{(i)},\cdots,\rho_{UN_c/SF-1}^{(i)}],\ \rho_n^{(i)}=E\left[\left|d(n)-\widetilde{s}^{(i)}(n)\right|^2\right].\tag{15}$$

When hard replica is used, the column vectors, $\overline{\mathbf{H}}_0$, $\overline{\mathbf{H}}_1$, ..., $\overline{\mathbf{H}}_{n-1}$, associated with already detected symbols are removed from $\overline{\mathbf{H}}$ in the $i$=0th iteration stage. On the other hand, in the $i$($i$>0)th iteration stage, all column vectors $\overline{\mathbf{H}}_0$, ..., $\overline{\mathbf{H}}_{n-1}$, $\overline{\mathbf{H}}_{n+1}$, ..., $\overline{\mathbf{H}}_{UN_c/SF-1}$ from $\overline{\mathbf{H}}$ are removed.

When soft replica is used, the MMSE weight vector can be updated by taking into account the residual ICI in each layer. Eq. (15) represents the impact of the residual ICI. By setting $\rho_n^{(i)}$ to 1, the $n$th symbol is detected. When $i$=0, the symbols with $n'=n\sim(UN_cSF-1)$ are undetected and hence, $\rho_{n'}^{(0)}$ becomes 1.

### C. QRM-MLD

The symbols to be detected are ranked according to their received SINRs which are computed using the MMSE weight matrix [14]. The SINR $\gamma_m$ of the $m$th symbol ($m$=0~ $N_c(U/SF)-1$) is given by

$$\gamma_m=\frac{(E_c/N_0)\left|\mathbf{W}_m\overline{\mathbf{H}}_m\right|^2}{\left\|\mathbf{W}_m\right\|+(E_c/N_0)\sum_{\substack{n'=0\\ \neq m}}^{UN_c/SF-1}\left|\mathbf{W}_m\overline{\mathbf{H}}_{n'}\right|^2},\tag{16}$$

where $\mathbf{W}_m$ is the is the $m$th low vector of the MMSE weight matrix given by Eq. (9). Below, without loss of generality, the transmitted symbols having the highest SINR is assumed to be the $(N_c(U/SF)-1)$th symbol, followed by the $(N_c(U/SF)-1)$th, $(N_c(U/SF)-2)$th,…,1st symbols.

Next, applying the QR decomposition to the equivalent channel matrix $\overline{\mathbf{H}}$, we have $\overline{\mathbf{H}} = \mathbf{QR}$, where $\mathbf{Q}$ is an $N_c \times N_c(U/SF)$ matrix satisfying $\mathbf{Q}^H\mathbf{Q}=\mathbf{I}$ and $\mathbf{R}$ is an $N_c(U/SF) \times N_c(U/SF)$ upper triangular matrix. The transformed frequency-domain received signal $\hat{\mathbf{Y}}$ is obtained as

$$\hat{\mathbf{Y}} = \mathbf{Q}^H \mathbf{Y} = \sqrt{2E_c/T_c}\,\mathbf{Rd} + \mathbf{Q}^H \mathbf{N}\,. \qquad (17)$$

The M-algorithm [15] is composed of $U(N_c/SF)$ stages, each corresponding to each symbol in a block. In each stage, the symbol replica candidates with low reliability are successively discarded based on the M-algorithm.

In each stage, the branch metric defined as the squared Euclidian distance from $\hat{\mathbf{Y}}$ is computed for all candidate symbols connected to each of $M$ surviving symbols in the previous stage and then, only a total of $M$ symbols having the smallest accumulated branch metrics are selected as the surviving symbols in the present stage and others are discarded. This process is repeated until the last stage. Finally, the symbol which has the smallest accumulated branch metric is chosen and a sequence of $U(N_c/SF)$ detected symbols is obtained by tracing back the surviving symbols until the first stage.

TABLE I. COMPUTER SIMULATION CONDITION.

| | | |
|---|---|---|
| Transmitter | Modulation | 16QAM |
| | block size | $N_c$=64 |
| | GI | $N_g$=16 |
| | Spreading sequence | Walsh sequence |
| | Spreading factor | $SF$=1, 64 |
| | No. of parallel codes | $U$=1~64 |
| | Scramble code | Long PN sequence |
| Channel | Fading type | Frequency-selective block Rayleigh |
| | Power delay profile | $L$=16-path uniform |
| Receiver | Channel estimation | Ideal |

## IV. COMPUTER SIMULATION

We assume 16 QAM date modulation, an FFT block size of $N_c$=64 chips, and a GI of $N_g$=16 chips. The channel is assumed to be a chip-spaced $L$=16-path frequency-selective block Rayleigh fading channel having uniform power delay profile. Ideal channel estimation is assumed.

### A. BER performance of full-code multiplexed DS-CDMA

Figure 3 shows the average BER performances as a function of average received bit energy-to-noise power spectrum density ratio $E_b/N_0(=SF(E_c/N_0)(1+N_g/N_c)/4)$ for the full code-multiplexing case ($SF$=$U$). Also plotted is the theoretical lower bound [16]. The cases of $SF$=1 (non-spread) and $SF$=64 (spread) are compared. The number of iterations in the iterative V-BLAST is set to $i$=1, since the use of single iteration provides sufficient performance improvement. For QRM-MLD, five cases of the number $M$ of surviving symbols in each stage are plotted, i.e., $M$=1, 4, 16, 64, and 256.

When iterative V-BLAST is used, full-code multiplexing ($SF$=$U$=64) provides better BER performance than non-spread SC transmission ($SF$=$U$=1). The reason for this is discussed below. In the case of non-spread SC transmission, the detection ordering is not necessary since the SINR is the same for all symbols. However, for the code multiplexing case ($SF$=$U$=64), the SINR of each symbol is different since a different orthogonal spreading code is assigned and the different interference is received from other symbols. Therefore, the detection of the symbols in decreasing order of the SINR is effective and provides better performance. When $SF$=$U$=64, the hard (soft) decision iterative V-BLAST achieves smaller required $E_b/N_0$ by 3.0(0.8) dB compared to that of non-spread SC transmission ($SF$=$U$=1).

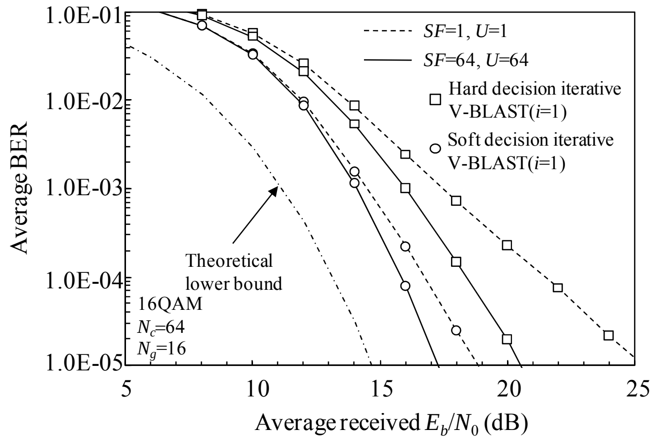
Similar to the case of V-BLAST, it can be seen from Fig. 3 (b) that when QRM-MLD is used, full-code multiplexing provides better BER performance than non-spread SC transmission and that the performance improvement become larger with reducing the number of surviving symbols. The reason for this is as follows. The probability of removing the correct symbol replica candidates at early stages can be reduced by detecting the symbols in decreasing order of the SINR. However, increasing the number of surviving symbol replica candidates can reduce this probability, leading to the reduced performance improvement. Using full-code multiplexing, the required $E_b/N_0$ for the average BER=$10^{-4}$ reduces by 6.3 and 1.1 dB when $M$=4 and 16 compared to that of non-spread SC transmission, respectively.

### B. Impact of the code-multiplexing order

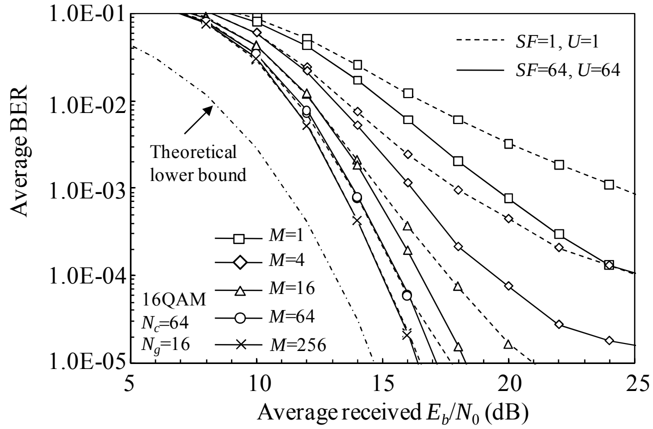
Figure 4 plots the required $E_b/N_0$ of frequency-domain block signal detection for achieving BER=$10^{-4}$ as a function of code multiplexing order $U$ for the case of $SF$=64. For comparison, the required $E_b/N_0$'s for MMSE-FDE and theoretical lower bound are also plotted. It can be seen that when $U$ is small, all frequency-domain block signal detection can reduce the required $E_b/N_0$ close to the theoretical lower bound. However, the required $E_b/N_0$ of the MMSE detection increases when $U$ is high for the given $SF$. On the other hand, the frequency-domain block signal detection combined with either iterative V-BLAST or QRM-MLD can reduce the required $E_b/N_0$ close to the theoretical lower bound even if the code-multiplexing order $U$ is high.

## V. CONCLUSIONS

In this paper, we proposed a frequency-domain block signal detection, which combines FDE and MIMO signal detection, for the reception of multi-code DS-CDMA signals. Various MIMO signal detection schemes can be combined with FDE. We showed that the frequency-domain block signal detection combined with either iterative V-BLAST or QRM-MLD provides a good BER performance and the full-code multiplexing ($SF$=$U$=64) can achieve better performance than the non-spread SC transmission ($SF$=$U$=1). We also showed that frequency-domain block signal detection can reduce the required $E_b/N_0$ compared to the conventional MMSE-FDE.

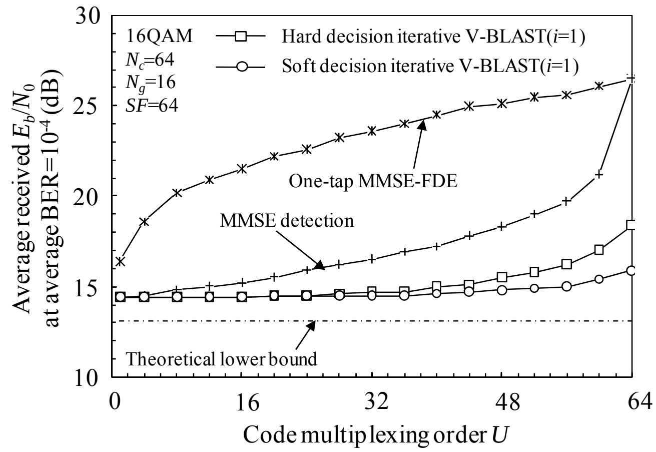



(a) Iterative V-BLAST detection.

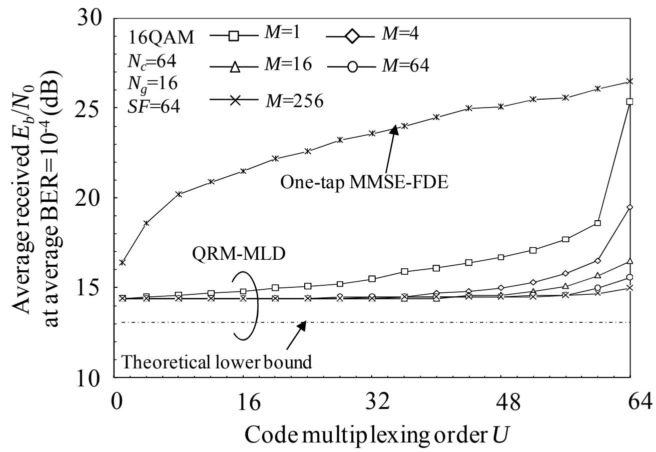



(b) QRM-MLD.

Figure 3. BER performance of full-code multiplexed DS-CDMA using frequency-domain block signal detection.




(a) MMSE detection and iterative V-BLAST detection.




(b) QRM-MLD.

Figure 4. Impact of the code-multiplexing order $U$ for the case of $SF$=64.

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