2-Step Maximum Likelihood Channel Estimation for Multicode DS-CDMA with Frequency-domain Equalization

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***Abstract*—Frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can provide better downlink bit error rate (BER) performance of direct sequence code division multiple access (DS-CDMA) than the conventional rake combining in a frequency-selective fading channel. FDE requires accurate channel estimation. In this paper, we propose a new 2-step maximum likelihood channel estimation (MLCE) for DS-CDMA with FDE. The 1st step uses the conventional MMSE-CE and the 2nd step carries out the MLCE using decision feedback from the 1st step. The BER performance improvement achieved by 2-step MLCE over conventional MMSE-CE is confirmed by computer simulation.**

Keywords; DS-CDMA, frequency-domain equalization, MMSE, channel estimation

I. INTRODUCTION

A very high-speed wireless access of e.g. 100 Mbps to 1 Gbps is demanded for 4th generation (4G) mobile communication systems [1]. In the present 3rd generation (3G) systems, direct sequence code division multiple access (DS-CDMA) is adopted as the wireless access technique [2]. However, since the wireless channel for such high speed data transmission is severely frequency-selective, the bit error rate (BER) performance of DS-CDMA with rake combining significantly degrades. The use of frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can improve the BER performance of DS-CDMA compared with the rake combining.

FDE requires accurate estimation of the channel transfer function. Pilot-assisted channel estimation (CE) can be performed in time- or frequency-domain. Time-domain pilot-assisted CE for single carrier transmission was proposed in [3]. After the channel impulse response is estimated according to the least-sum-of-squared-error (LSSE) criterion, the channel transfer function is obtained by applying fast Fourier transform (FFT). Frequency-domain pilot assisted CE was proposed in [4], [5]. The received pilot signal is transformed into the frequency-domain pilot signal and then the pilot modulation is removed using zero forcing (ZF) technique. As the pilot signal, the Chu sequence [6] that has the constant amplitude in both time- and frequency-domain is used. However, the number of the Chu sequences is limited. Therefore, we use the PN sequence as pilot. However, since the frequency spectrum of the PN sequence is not constant, the noise enhancement is produced if the ZF-CE is used [7]. The noise enhancement can be prevented by using the minimum mean square error (MMSE)-CE [7]. Using MMSE-CE, the channel estimation accuracy is almost insensitive to the pilot chip sequence. In this paper, to further improve the estimation accuracy, we propose a 2-step maximum likelihood channel estimation (MLCE). The 1st step uses the conventional MMSE-CE and the 2nd step carries out the MLCE using decision feedback from the 1st step. We evaluate the BER performance of multicode DS-CDMA using 2-step MLCE in a frequency selective Rayleigh fading channel by computer simulation.

II. TRANSMISSION SYSTEM MODEL

A. Overall transmission system model

The transmission system model for multicode DS-CDMA with FDE is illustrated in Fig 1. Throughout the paper, the chip-spaced discrete time representation is used.

At the transmitter, a binary data sequence is transformed into data-modulated symbol sequence and then converted to parallel streams by serial-to-parallel (S/P) conversion. Then, the transmit chip sequence is divided into a sequence of blocks of N_c/SF symbols $\{d_{n,u}(m);m=0\sim N_c/SF-1\}$, where SF is spreading factor and $\{d_{n,u}(m)\}$ is the data symbol sequence of the uth (u=0~U−1) code in the nth (n=0~N−1) block. $d_{n,u}(m)$ is spread by multiplying it with an orthogonal spreading sequence $\{c_u(t);t=0\sim SF-1\}$. The resultant U chip sequences are multiplexed and further multiplied by a common scramble sequence $\{c_{scr}(t);t=\ldots,-1,0,1,\ldots\}$ to make the resultant multicode DS-CDMA signal like white-noise. The last N_g chips of each block is copied as a cyclic prefix and inserted into the guard interval (GI) placed at the beginning of each block. The block structure after the GI insertion is illustrated in Fig. 2. For channel estimation, one pilot block is transmitted every N−1 data blocks for channel estimation as shown in Fig. 3.

The GI-inserted chip block is transmitted over a frequency-selective fading channel and is received at a receiver. After the removal of the GI, the received chip block is decomposed by N_c-point FFT into N_c frequency components and then FDE is carried out. After FDE, inverse FFT (IFFT) is applied to obtain the time-domain received chip block for despreading. Finally, data-demodulation is carried out on the received data.

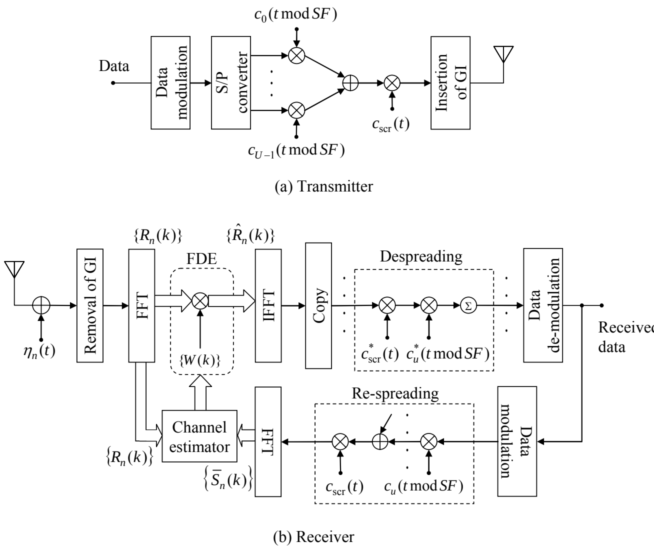

Figure 1. Transmitter/receiver structure for DS-CDMA with FDE.

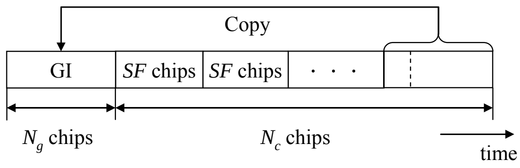

Figure 2. Block structure.

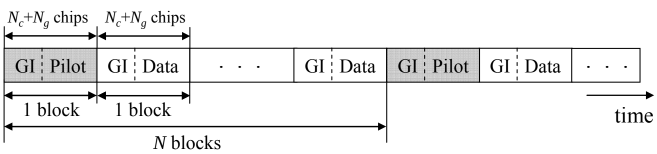

Figure 3. Transmit block structure.

B. Signal representation

The nth chip block $\{s_n(t);t=0\sim N_c-1\}$ can be expressed, using the equivalent lowpass representation, as

$$s_n(t)=\left[\sum_{u=0}^{U-1} d_{n,u}\left(\left\lfloor \frac{t}{SF}\right\rfloor\right) c_u(t \bmod SF)\right] c_{\mathrm{scr}}(t)\,, \tag{1}$$

where $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x. After inserting the GI of N_g chips, the nth chip block is transmitted. The propagation channel is assumed to be a frequency-selective block fading channel having chip-spaced L discrete path, each subjected to independent fading. We assume that the channel gains do not vary over N blocks. The impulse response $h(t)$ of multipath channel can be expressed as

$$h(t)=\sum_{l=0}^{L-1} h_l \delta(t-\tau_l)\,, \tag{2}$$

where h_l and τ_l are the complex-valued path gain and time delay of the lth path (l=0~L−1), respectively , with $\sum_{l=0}^{L-1} E[|h_l|^2]=1$ (E[.] denotes the ensemble average operation). In this paper, we assume that the channel impulse response is present within the GI length.

The nth received chip block $\{r_n(t);t=-N_g\sim N_c-1\}$ can be expressed as

$$r_n(t)=\sum_{l=0}^{L-1}\sqrt{2P}h_l \hat{s}_n(t-\tau_l)+\eta_n(t)\,, \tag{3}$$

where $P=E_c/T_c$ is the signal power with E_c and T_c denoting the chip energy and chip duration, respectively, and $\eta_n(t)$ is a zero-mean complex Gaussian process with a variance of $2N_0/T_c$ with N_0 being the single-sided power spectrum density of the additive white Gaussian noise (AWGN) process.

C. MMSE-FDE

After the removal of the GI, the received chip block is decomposed by N_c-point FFT into N_c frequency components. The kth frequency component of the nth (n=0~N−1) block can be written as

$$\begin{aligned} R_n(k)&=\sum_{t=0}^{N_c-1} r_n(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ &=H(k)S_n(k)+\Pi_n(k)\,, \end{aligned} \tag{4}$$

where $H(k)$ is the channel gain, $S_n(k)$ is the kth frequency component of the transmitted chip block, and $\Pi_n(k)$ is the noise due to zero-mean AGWN with variance $2\sigma^2=2N_0N_c/T_c$. They are given by

$$\begin{cases} S_n(k)=\sum_{t=0}^{N_c-1} s_n(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ H(k)=\sum_{l=0}^{L-1}\sqrt{2P}h_l \exp\left(-j2\pi k\frac{\tau_l}{N_c}\right)\\ \Pi_n(k)=\sum_{t=0}^{N_c-1}\eta_n(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \end{cases}. \tag{5}$$

One-tap MMSE-FDE is carried out as

$$\hat{R}_n(k)=W(k)R_n(k)\,, \tag{6}$$

where $W(k)$ is the MMSE-FDE weight and is given by [8], [9]

$$W(k)=\frac{H^*(k)}{UN_c|H(k)|^2+2\sigma^2}\,, \tag{7}$$

where * denotes the complex conjugate operation. $H(k)$ and σ^2 are unknown to the receiver. We need to estimate them. In the following section, we describe the proposed 2-step MLCE.

N_c-point IFFT is applied to transform the frequency-domain signal $\{\hat{R}_n(k);k=0\sim N_c-1\}$ into time-domain chip block $\{\hat{r}_n(t);t=0\sim N_c-1\}$:

$$\hat{r}_n(t)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{R}_n(k)\exp\left(j2\pi t\frac{k}{N_c}\right). \quad (8)$$

Finally, despreading is carried out on $\{\hat{r}_n(t)\}$, giving $\{\hat{d}_{n,u}(m); m=0\sim N_c/SF-1, u=0\sim U-1\}$:

$$\hat{d}_{n,u}(m)=\frac{1}{SF}\sum_{t=mSF}^{(m+1)SF-1}\hat{r}_n(t)c_u^*(t\bmod SF)c_{\mathrm{scr}}^*(t), \quad (9)$$

which is the decision variable for data demodulation on $\{\hat{d}_{n,u}(m)\}$.

III. 2-STEP MLCE

A. Maximum likelihood estimation

Joint conditional probability density function $p(\{R_n(k);n=0\sim N-1\}|H(k),\{S_n(k);n=0\sim N-1\})$ of the kth frequency component, for the given $H(k)$ and $\{S_n(k)\}$, can be given as [10]

$$p(\{R_n(k)\}\,|\,H(k),\{S_n(k)\}) = \prod_{n=0}^{N-1}\frac{1}{2\pi\sigma^2}\exp\left(-\frac{|R_n(k)-H(k)S_n(k)|^2}{2\sigma^2}\right). \quad (10)$$

Log-likelihood function $L(k)$ is obtained from Eq.(10) as

$$L(k)=\log[p(\{R_n(k)\}\,|\,H(k),\{S_n(k)\})] = N\log\left(\frac{1}{2\pi\sigma^2}\right)-\frac{1}{2\sigma^2}\sum_{n=0}^{N-1}|R_n(k)-H(k)S_n(k)|^2. \quad (11)$$

We want to find the maximum likelihood estimate $H_{\mathrm{ML}}(k)$ that maximizes $L(k)$. Solving $\partial L(k)/\partial H(k)=0$, $H_{\mathrm{ML}}(k)$ is obtained as

$$H_{\mathrm{ML}}(k)=\left(\sum_{n=0}^{N-1}R_n(k)S_n^*(k)\right)\Big/\sum_{n=0}^{N-1}|S_n(k)|^2. \quad (12)$$

B. 2-step channel estimation

In Eq.(12), $\{S_n(k)\}$ is unknown. Therefore, we first apply the pilot-assisted MMSE-CE [7] and carry out MMSE-FDE to obtain the tentative decision symbol sequence (1st step). Then, the chip sequence replica is generated for channel estimation based on Eq.(12) (2nd step). This 2-step channel estimation is called 2-step MLCE in the paper. 2-step MLCE is illustrated in Fig. 4.

1) 1st step

The kth frequency component of the received pilot chip block can be represented as

$$R_0(k)=H(k)C(k)+\Pi_0(k), \quad (13)$$

where $C(k)$ is the kth frequency component of the transmitted pilot chip block $\{c(t);t=0\sim N_c-1\}$. $C(k)$ is given by

$$C(k)=\sum_{t=0}^{N_c-1}\sqrt{U}c(t)\exp\left(-j2\pi k\frac{t}{N_c}\right). \quad (14)$$

The instantaneous channel gain estimate $\tilde{H}^{(1)}(k)$ obtained by MMSE-CE is given by

$$\tilde{H}^{(1)}(k)=X(k)R_0(k), \quad (15)$$

where

$$X(k)=\frac{C^*(k)}{|C(k)|^2+(P/\sigma^2)^{-1}}, \quad (16)$$

is the reference to remove the pilot modulation [7]. The signal power P and the noise power σ^2 must be known. They can be estimated following to [11].

The instantaneous channel gain estimate $\{\tilde{H}^{(1)}(k);k=0\sim N_c-1\}$ is noisy. The noise can be suppressed by applying delay time-domain windowing technique [12], [13]. $\{\tilde{H}^{(1)}(k);k=0\sim N_c-1\}$ is transformed by N_c-point IFFT into the instantaneous channel impulse response $\{\tilde{h}^{(1)}(\tau);\tau=0\sim N_c-1\}$ as

$$\tilde{h}^{(1)}(\tau)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}^{(1)}(k)\exp\left(j2\pi\tau\frac{k}{N_c}\right). \quad (17)$$

The real channel impulse response is present only within the GI length, while the noise is present over an entire delay-time range. Replacing $\tilde{h}^{(1)}(\tau)$ with zero's for $N_g\le\tau<N_c$ and applying N_c-point FFT, the improved channel gain estimate $\{\bar{H}^{(1)}(k);k=0\sim N_c-1\}$ is obtained as

$$\bar{H}^{(1)}(k)=\sum_{\tau=0}^{N_g-1}\tilde{h}^{(1)}(\tau)\exp\left(-j2\pi k\frac{\tau}{N_c}\right). \quad (18)$$

The MMSE-FDE weight is computed using Eq.(7) with replacing $H(k)$ by $\bar{H}^{(1)}(k)$ for carrying out MMSE-FDE (see Eq.(6)). After FDE, $\{\hat{R}_n(k);n=1\sim N-1\}$ is transformed by N_c-point IFFT into the time-domain chip block, followed by despreading and tentative data symbol decision.

The tentative decision symbol sequence $\{\bar{d}_{n,u}^{(1)}(m);m=0\sim N_c/SF-1,u=0\sim U-1\}$, is spread to obtain the transmitted chip block replica $\{\bar{s}_n^{(1)}(t);t=0\sim N_c-1\}$:

$$\bar{s}_n^{(1)}(t)=\left[\sum_{u=0}^{U-1}\bar{d}_{n,u}^{(1)}\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)c_u(t\bmod SF)\right]c_{\mathrm{scr}}(t). \quad (19)$$

Applying N_c-point FFT to $\{\bar{s}_n^{(1)}(t)\}$, the kth frequency component of the transmitted chip block replica is obtained as

$$\bar{S}_n^{(1)}(k)=\sum_{t=0}^{N_c-1}\bar{s}_n^{(1)}(t)\exp\left(-j2\pi k\frac{t}{N_c}\right). \quad (20)$$

2) 2nd step

Since $\{S_n(k)\}$ in Eq.(12) is unknown to the receiver when $n \neq 0$, $\{S_n(k)\}$ is replaced by $\{\bar{S}_n^{(1)}(k)\}$. $\widetilde{H}^{(2)}(k)$ is obtained, from Eq.(13), as

$$\widetilde{H}^{(2)}(k) = \frac{R_0(k)C^*(k) + \sum_{n=1}^{N-1} R_n(k)\{\bar{S}_n^{(1)}(k)\}^*}{|C(k)|^2 + \sum_{n=1}^{N-1} \left|\bar{S}_n^{(1)}(k)\right|^2}. \qquad (21)$$

By applying delay time-domain windowing technique to $\{\widetilde{H}^{(2)}(k); k = 0 \sim N_c - 1\}$ as in the 1st step, the improved channel gain estimate $\{\bar{H}^{(2)}(k); k = 0 \sim N_c - 1\}$ is obtained. MMSE-FDE is performed again using MMSE-FDE weight obtained using $\bar{H}^{(2)}(k)$, followed by despreading and final data decision to obtain the received data symbol sequence $\{\bar{d}_{n,u}^{(2)}(m); m = 0 \sim N_c/SF - 1, u = 0 \sim U - 1\}$.

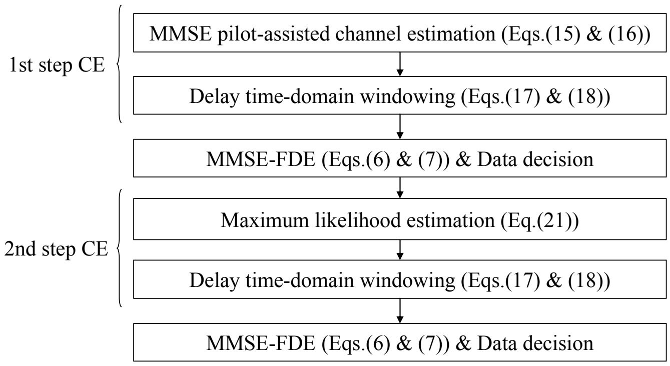

Figure 4. 2-step MLCE.

IV. Computer Simulation

The simulation condition is shown in Table 1. We assume 16QAM data modulation, an FFT block size of N_c=256 chips and a GI of N_g=32 chips. One pilot block is transmitted every 15 data blocks (i.e., N=16). We assume the spreading factor SF=16 and an L=16-path frequency-selective block Rayleigh fading channel having exponential power delay profile.

The simulated BER performance of multicode DS-CDMA with MMSE-FDE is plotted in Fig. 5 for U=1 and 16 as a function of the average received bit energy-to-AWGN noise power spectrum density ratio E_b/N_0, defined as E_b/N_0=$(1/\log_2 K)SF(E_c/N_0)(1+N_g/N_c)(N/(N-1))$, where K is the modulation level. We have assumed block fading, where the channel gains stay constant over an interval of N chip blocks (i.e., the maximum Doppler frequency $f_D \rightarrow 0$). For comparison, the BER performances with conventional MMSE-CE [7] and ideal CE are also plotted. With conventional MMSE-CE [7], the E_b/N_0 loss from the ideal CE case for BER=10^{-4} is about 0.8 (0.9) dB when U=1 (16). This E_b/N_0 loss includes a pilot insertion loss of 0.28 dB. The use of 2-step MLCE improves the BER performance and reduces the E_b/N_0 loss from the ideal CE to about 0.4 dB when U=1 and 16.

The channel estimation accuracy may depend on the channel frequency-selectivity. The simulated BER is plotted in Fig. 6 with decay factor α as a parameter for the full code-multiplexing case (U=SF=16). For comparison, the BER performances with conventional MMSE-CE [7] and ideal CE are also plotted. Regardless of decay factor α, 2-step MLCE provides better BER performance than conventional MMSE-CE [7] and reduces the E_b/N_0 loss from the ideal CE to about 0.4 dB.

Fig. 7 shows the effect of fading rate on the achievable BER as a function of the normalized Doppler frequency $f_D(N_c+N_g)T_c$ at E_b/N_0=24dB for the full code-multiplexing case (U=SF=16). We have assumed that the channel gains vary over an interval of N chip blocks, but stay constant during each chip block. For comparison, the BER performance using conventional MMSE-CE [7] is also plotted. It is seen from Fig. 7 that 2-step MLCE provides better BER performance than conventional MMSE-CE when $f_D(N_c + N_g)T_c < 7\times10^{-4}$ (this corresponds to a terminal moving speed of 52.5 km/h for a chip rate $1/T_c$ of 100Mcps and 5GHz carrier frequency). However, for a higher fading rate, the proposed MLCE is inferior to conventional MMSE-CE since it assumes the constant channel gain over an N chip block interval.

TABLE I. SIMULATION CONDITION

Transmitter	Data modulation	16QAM
	Number of FFT points	N_c = 256
	Guard interval length	N_g = 32
	Spreading sequence	Product of Walsh sequence and PN sequence
	Spreading factor	SF = 16
	Code multiplexing order	U = 1, 16
	Pilot chip sequence	PN sequence
Channel	Fading	Frequency-selective Rayleigh fading
	Power delay profile	L=16-path exponential power delay profile
		Decay factor α=0,3,∞dB
Receiver	Frequency-domain equalization	MMSE
	Channel estimation	2-step MLCE

V. Conclusions

In this paper, we proposed the 2-step MLCE for multicode DS-CDMA with MMSE-FDE and evaluated by computer simulation the achievable BER performance in a frequency-selective block Rayleigh fading channel. It was shown that the proposed 2-step MLSE improves the BER performance compared to conventional MMSE-CE in a slow fading environment. The required E_b/N_0 loss for BER=10^{-4} from the ideal CE is only 0.4 dB (about 0.28 dB is due to the pilot insertion) irrespective of code multiplexing order and channel decay factor.

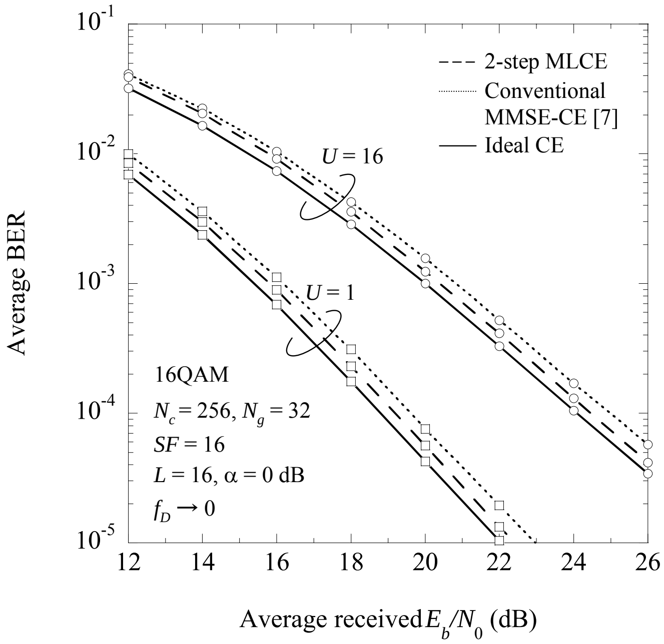

Figure 5. Average BER performance.

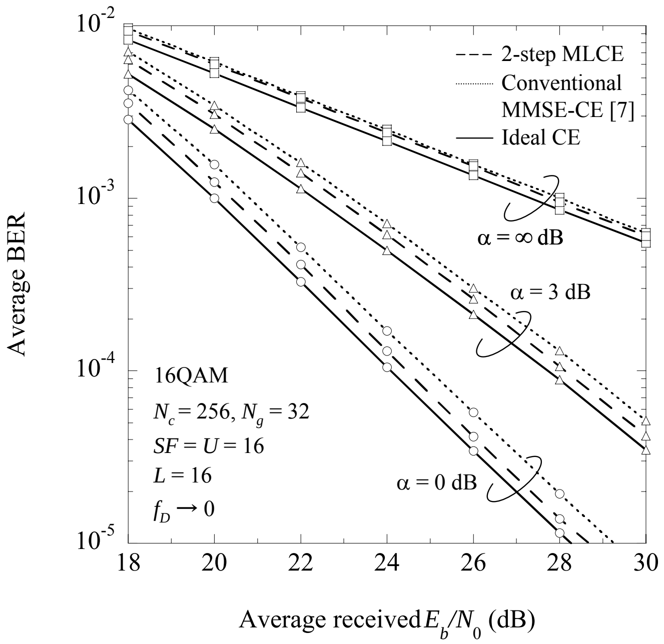

Figure 6. Effect of channel frequency-selectivity.

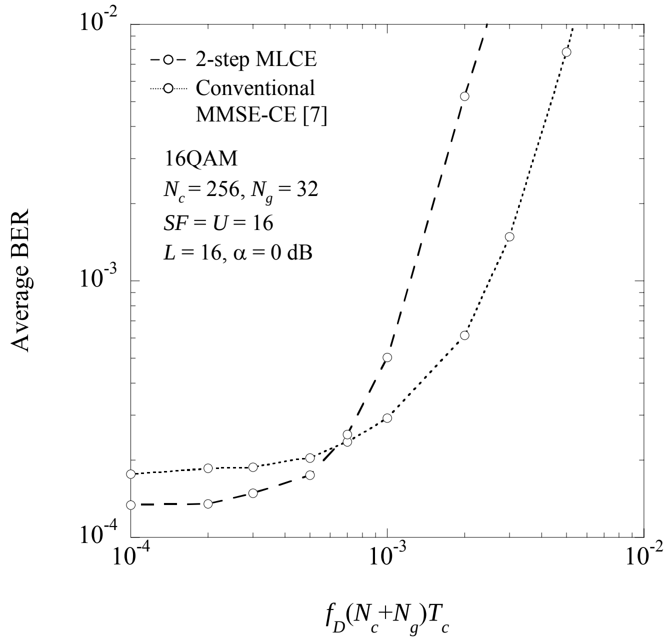

Figure 7. Effect of fading rate.

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