DIVERSITY-CODING-ORTHOGONALITY TRADEOFF FOR CODED MC-CDMA WITH HIGH LEVEL MODULATION

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ABSTRACT

In MC-CDMA, the data rate can be increased by reducing the spreading factor *SF* or by allowing multicode transmission. In this paper, we evaluate by computer simulations which gives a better bit error rate (BER) performance - lower *SF* or multicode operation - when high level modulation is used in addition to error control coding. For a coded system in a frequency selective channel, there is a tradeoff between frequency diversity gain due to the spreading of symbols, coding gain due to better frequency interleaving effect and orthogonality destruction. It is shown that for QPSK, the performance of OFDM (MC-CDMA with *SF*=1) is almost the same as that of a fully spread MC-CDMA system. However, for 16QAM and 64QAM, the BER performance is better for lower *SF* unlike the uncoded system, wherein higher *SF* gives a better BER.

1. INTRODUCTION

Recently, the combination of multicarrier (MC) modulation based on orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA), called MC-CDMA [1, 2], has gained a lot of attention because of its ability to allow high data rate transmission in a harsh mobile environment and has emerged as the most promising candidate for the next generation mobile communication systems [3]. In MC-CDMA, each user's data-modulated symbol to be transmitted is spread over a number of subcarriers using an orthogonal spreading code defined in the frequency-domain. Since the received signal suffers from frequency selective multipath fading, the orthogonality among different users' signals is partially lost, producing a large multiuser interference (MUI). However, the orthogonality property can be partially restored while achieving the frequency diversity effect by using the minimum mean square error frequency domain equalization (MMSE-FDE) [4] and hence, a better bit error rate (BER) performance can be achieved.

The next generation mobile communications systems will be characterized by very high speed data transmissions. For high speed data transmissions, high level modulation like 16 quadrature amplitude modulation (16QAM) and 64QAM becomes inevitable. The spreading factor *SF* can be lowered or multicode transmission, with multiple codes assigned to a user, can also be applied to increase the data rate. OFDM can be viewed as a special case of MC-CDMA with *SF*=1. With higher *SF*, the orthogonality destruction is severer in a frequency selective channel. But at the same time, the frequency diversity effect is also higher. In [5], the uncoded BER performance of multicode MC-CDMA and OFDM is evaluated for binary phase shift keying (BPSK) data modulation and concluded that multicode MC-CDMA provides a better BER for the same data rate and bandwidth. In all types of data transmission systems, some form of error control is needed to improve the transmission performance. Turbo coding has been found to provide strong error correction capabilities. In [6], the trade-off between channel coding and spreading in MC-CDMA is evaluated when convolutional coding and quaternary phase shift keying (QPSK) data modulation is used. It is concluded [6] that for a full load system, MC-CDMA provides a better BER performance for high code rates. However, in [5] and [6], higher level modulation has not been considered. With higher level modulation, the Euclidean distance between the symbols are smaller and the orthogonality destruction is a major problem. However, it is not known as to whether it is better to reduce the spreading factor or use a high spreading factor and allow multicode transmission when high level modulation is applied in addition to channel coding. In this paper, we evaluate by computer simulations, the coded BER performance of MC-CDMA with high level modulation when turbo coding is used for error control. For a fair comparison we keep the transmission rate fixed as that attainable with an OFDM system. The purpose of the paper is to find out the uncoded BER performance dependence of MC-CDMA on *SF* and see how the trend changes when channel coding is applied.

The remainder of the paper is organized as follows. Sect. 2 presents the transmission system model and shows how the soft decision values are generated for turbo decoding. The computer simulation results are presented and discussed on diversity-coding-orthogonality tradeoff in Sect. 3. Sect. 4 concludes the paper.

2. TRANSMISSION SYSTEM MODEL

The transmission system model is shown in Fig. 1. The information sequence of length K is turbo coded with a coding rate R and modulated as QPSK, 16QAM or 64QAM symbol sequence. Let $d(n)$ be the nth modulated symbol, with symbol length T, in the sequence. We consider MC-CDMA having N_c orthogonal subcarriers. The data is spread using the frequency-domain orthogonal spreading code with spreading factor *SF*. Throughout the paper, T_c-spaced discrete-time representation of the MC-CDMA signal is used, where T_c is the sampling interval. Without loss of generality, we consider the time interval of one signaling period, i.e., $0 \le t < N$ with $N=N_c+N_g$, where N_c and N_g are respectively the window size of fast Fourier transform (FFT) (or the number of subcarriers) and the guard interval (GI). The modulated symbol sequence is serial-to-parallel (S/P) converted into C streams $\{d_c(n);\ c$=0~C-1$\}$. For each parallel stream, the signal is again S/P converted to N_c/SF streams; each symbol is then copied SF times and spread by multiplying with an orthogonal code $\{c_{oc,c}(k),\ c=0\sim C-1,\ k=0\sim SF-1\}$ with spreading factor SF. The C different streams are then added (C is the code multiplexing order) and further multiplied by a long scramble sequence $\{c_{scr}(k)\}$. The low-pass equivalent of the code multiplexed signal to be transmitted on the kth subcarrier can be written as

$$x(k)=\sqrt{\frac{2P}{SF}}\sum_{c=0}^{C-1}c_{oc,c}(k \bmod SF)c_{scr}(k)d_c\left(\left\lfloor\frac{k}{SF}\right\rfloor\right), \quad (1)$$

where P is the transmit power per spreading code and $\lfloor a\rfloor$ denotes the largest integer smaller than or equal to a. N_c-point inverse FFT (IFFT) is applied to the sequence $\{x(k);k=0\sim N_c-1\}$ to generate the MC-CDMA signal $\{s(t);t=0\sim N_c-1\}$ in time-domain:

$$s(t)=\sum_{k=0}^{N_c-1}x(k)\exp\left(j2\pi kt/N_c\right), \quad (2)$$

where t represents the sample position within the signaling interval $0\le t<N_c$. After insertion of the N_g-sample GI, the resultant MC-CDMA signal $\{\tilde{s}(t);t=-N_g\sim N_c-1\}$ is transmitted over a propagation channel, where $\tilde{s}(t)=s(t \bmod N_c)$.

A T_c-spaced time delay model for the propagation channel is assumed. M-branch antenna diversity reception is considered. Assuming L independent propagation paths with distinct time delays $\{\tau_l\}$, the impulse response $\xi_m(\tau)$ of the multipath channel seen at the mth receive antenna, m=0~M-1, may be expressed as

$$\xi_m(\tau)=\sum_{l=0}^{L-1}\xi_{m,l}\delta(\tau-\tau_l) \quad (3)$$

with $\sum_{l=0}^{L-1}\mathrm{E}[|\xi_{m,l}|^2]=1$, where $\delta(t)$ is the delta function and E[.] denotes the ensemble average operation. Time dependency of the channel has been dropped for simplicity.

At the receiver, ideal sampling timing is assumed. The MC-CDMA signal received on the mth antenna is sampled to obtain $\{\tilde{r}_m(t);t=-N_g\sim N_c-1\}$, which is expressed as

$$\tilde{r}_m(t)=\sum_{l=0}^{L-1}\xi_{m,l}\tilde{s}(t-\tau_l)+\eta_m(t), \quad (4)$$

where $\eta_m(t)$ represents the additive white Gaussian noise (AWGN) process with the single sided power spectrum density N_0. The N_g-sample GI is removed and the N_c-point FFT is applied to decompose the received MC-CDMA signal into the N_c subcarrier components $\{R_m(k);k=0\sim N_c-1\}$:

$$R_m(k)=\frac{1}{N_c}\sum_{t=0}^{N_c-1}\tilde{r}_m(t)\exp\left(-j2\pi kt/N_c\right) \quad (5)$$

for m=0~M-1. If the channel gain at the kth subcarrier on the mth antenna is $H_m(k)$, the kth subcarrier component $R_m(k)$ received on the mth antenna can be written as

$$R_m(k)=H_m(k)x(k)+\Pi_m(k), \quad (6)$$

where $\{H_m(k);\ k$=0~N_c-1$\}$ and $\{\Pi_m(k);\ k$=0~N_c-1$\}$ are respectively the Fourier transforms of the channel impulse response $\xi_m(\tau)$ and the AWGN process $\eta_m(t)$. They are given by

$$\begin{cases}H_m(k)=\sum_{l=0}^{L-1}\xi_{m,l}\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right)\\ \Pi_m(k)=\frac{1}{N_c}\sum_{t=0}^{N_c-1}\eta_m(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases}. \quad (7)$$

$\{H_m(k);\ m$=0~M-1$\}$ on the kth subcarrier are the independent and identically distributed (iid) complex random variables with zero mean and unit variance.

MMSE-FDE and antenna diversity combining is performed together by multiplying the received signal in Eq. (6) by the equalization weight $w_m(k)$ [7]

$$w_m(k)=\frac{H_m^*(k)}{\sum_{m=0}^{M-1}|H_m(k)|^2+[(C/SF)(E_s/N_0)]^{-1}}, \quad (8)$$

where E_s is the symbol energy with $E_s=PT_cN_c$. The kth subcarrier component after MMSE-FDE is $\tilde{R}(k)=\tilde{H}(k)x(k)+\tilde{\Pi}(k)$ for k=0~N_c-1, where $\tilde{H}(k)=\sum_{m=0}^{M-1}H_m(k)w_m(k)$ and

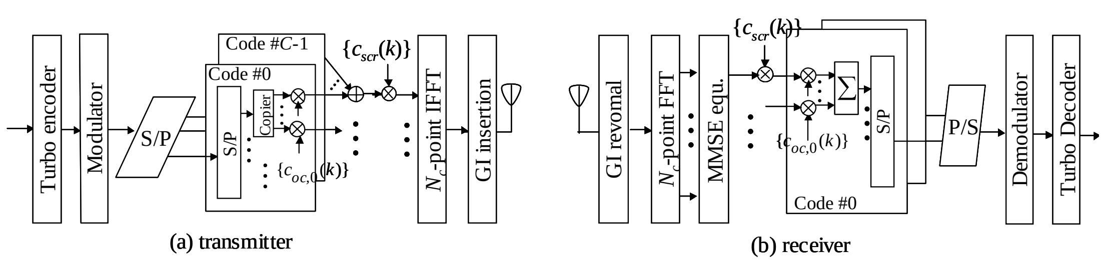


Fig.1. Transmission system model

$\tilde{\Pi}(k)=\sum_{m=0}^{M-1}\Pi_m(k)w_m(k)$. Frequency-domain despreading is applied to obtain

$$\begin{aligned}\hat{d}_c(n)&=\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{R}(k)\{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^* \\ &=\sqrt{\frac{2P}{SF}}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)\right)d_c(n)+\mu_{ICI}(n)+\mu_{noise}(n)\end{aligned} \quad .(9)$$

for n=0~N_c/SF and c=0~C-1. The first term represents the desired signal component and the second and third terms are the inter-code-interference (ICI) and AWGN component respectively. $\mu_{ICI}(n)$ and $\mu_{noise}(n)$ are given by

$$\begin{cases}\mu_{ICI}(n)=\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^* \\ \qquad \times\sqrt{\frac{2P}{SF}}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)\sum_{\substack{c'=0\\ \neq c}}^{C-1}x_{c'}(k)\{c_{oc,c'}(k \bmod SF)c_{scr}(k)\} \\ \mu_{noise}(n)=\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^*\tilde{\Pi}(k)\end{cases} \quad .(10)$$

The equivalent channel gain for each symbol is $\hat{H}(k)=\sqrt{\frac{2P}{SF}}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)\right)$ and the frequency diversity gain is a function of SF. After parallel-to-serial (P/S) conversion, the sample sequence is soft demodulated using the log-likelihood ratio (LLR) approximation [8] given by

$$L(b)=\frac{\left|\hat{d}_c(n)-\hat{H}(n)\hat{s}_0\right|^2}{2\sigma^2}-\frac{\left|\hat{d}_c(n)-\hat{H}(n)\hat{s}_1\right|^2}{2\sigma^2}, \qquad (11)$$

for the bth bit in the nth symbol; b=0~1, 3 and 5 bits for QPSK, 16QAM and 64QAM, respectively. Here, $\hat{s}_0$ (or $\hat{s}_1$) is the candidate symbol, with 0 (or 1) in the bth bit position, for which the Euclidean distance from the despread symbol $\hat{d}_c(n)$ is minimum. σ^2 is the Gaussian approximated ICI plus noise variance given by

$$\begin{aligned}\sigma^2=\frac{N_0}{T_cN_cSF}&\left[\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\sum_{m=0}^{M-1}\left|w_m(k)\right|^2\right. \\ &\left.+\left(\frac{C-1}{SF}\frac{E_s}{N_0}\right)\left\{\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\left|\tilde{H}(k)\right|^2-\left|\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)\right|^2\right\}\right]\end{aligned} . \ (14)$$

These LLR values are computed for c=0~C-1 and for all the bits in the symbol. Turbo decoding is performed using these LLR values as soft input.

3. SIMULATION RESULTS

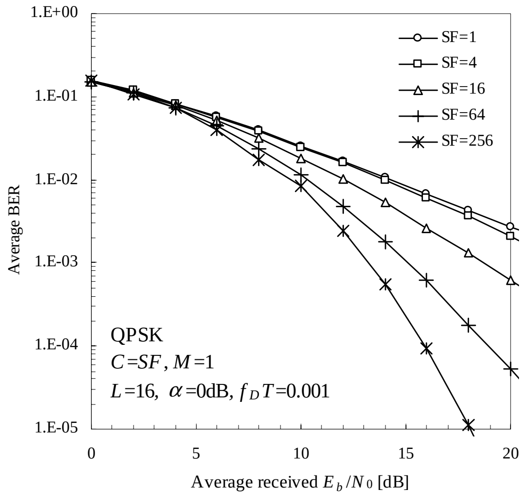
Table 2 summarizes the computer simulation conditions. We assume MC-CDMA using N_c=256 subcarriers, GI of N_g=32, and coherent QPSK, 16QAM and 64QAM data-modulation. A frequency-selective Rayleigh fading channel having L=16-path exponential power delay profile with decay factor α and $\tau_l = l$ is assumed. Unless otherwise stated, the decay factor α is taken to be 0dB. The normalized maximum Doppler frequency f_DT=0.001, which corresponds to a mobile velocity of about 100km/hr when the carrier frequency is 5GHz and the transmission rate is 100M symbols/sec; T is the MC-CDMA signaling period including GI. Uncorrelated, time-varying Rayleigh faded paths are generated using Dent's model [9]. Walsh Hadamard codes are used as short orthogonal codes. We assume the full load condition with SF=C to maintain the data rate fixed as that of an OFDM system (MC-CDMA with SF=1). A rate ½ turbo encoder with a constraint length 4 and (13, 15) recursive systematic convolutional (RSC) component encoders is assumed. Log-MAP decoding with 8 iterations is carried out at the receiver. The data sequence length is taken to be 1024 bits. A 64x64-bit block channel interleaver is assumed. The estimations of the channel gains, AWGN power spectrum density and the number of multiplexed codes are assumed to be ideal.

We show how the average BER changes with the change in SF when C=SF for different modulation levels. We perform the analysis first for the uncoded case and then for the coded case when R= ½ turbo code is used for error correction. With higher SF, the frequency diversity gain is higher but at the same time the orthogonality destruction is also severer. So, we try to find the SF which gives the lowest BER for the same data rate and bandwidth under the same propagation conditions.

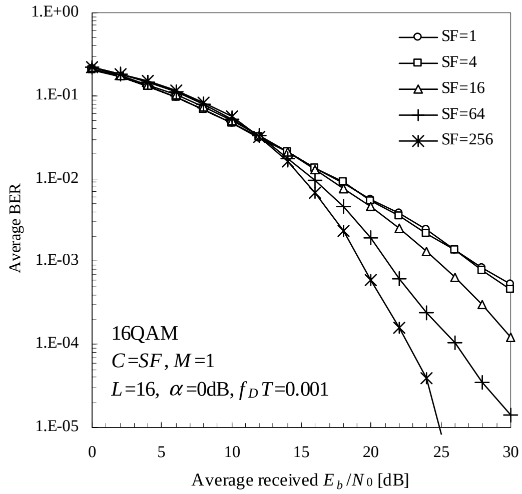
Table 2: Simulation conditions

Turbo coding	Rate=1/2 (13, 15) RSC encoder Log-MAP decoding with 8 iterations	
Channel Encoder	64 x 64 block encoder	
Data modulation	Coherent QPSK, 16QAM, 64QAM	
MC-CDMA	No. of subcarriers	N_c=256
	GI	N_g=32
	Spreading factor	SF=1~256
Channel model	Rayleigh fading (L=16, $\tau_l = l$) f_DT=0.001	

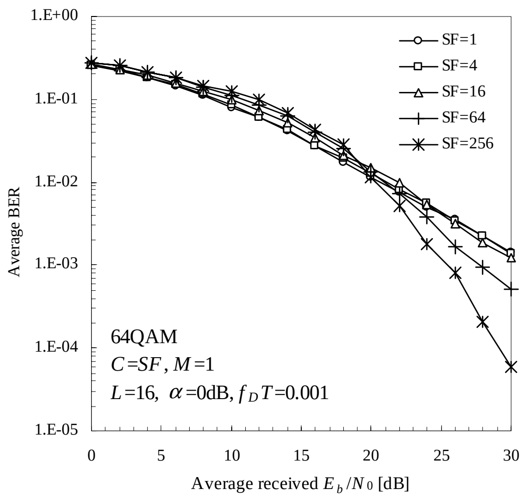
Figure 2(a)~(c) plot the average BER as a function of the average received signal energy per bit-to-the noise power spectral density ratio E_b/N_0 with SF as a parameter for QPSK, 16QAM and 64QAM when M=1. The power penalty due to GI insertion has been included in the E_b/N_0. From Fig. 2(a), we see that for QPSK modulation, the BER improves with the increase in SF and is the lowest for SF=256. As said earlier, the orthogonality destruction is severer for higher SF in a frequency selective channel, but MMSE-FDE is applied which restores orthogonality to a certain extent. For SF=1 (OFDM), there is no diversity gain and no orthogonality destruction. For SF>1, there is a frequency diversity gain resulting due to the spreading of each symbol over more subcarriers, but at the same time the orthogonality among the codes is partially destroyed. For 16QAM and 64QAM, however, the result is little different. In the noise dominant region (lower E_b/N_0 region), the average BER is better for lower SF. The Euclidean distance between the different symbols



(a) QPSK modulation

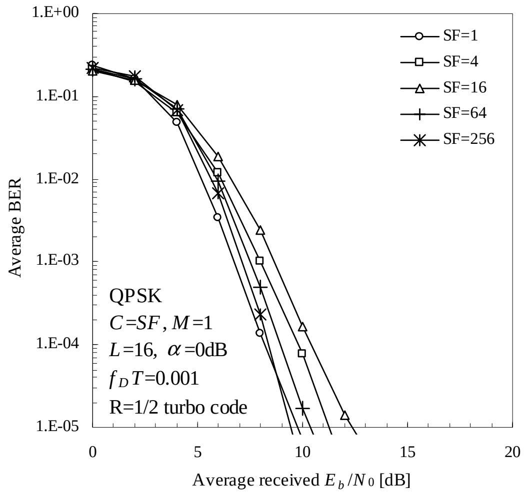


(b) 16QAM modulation

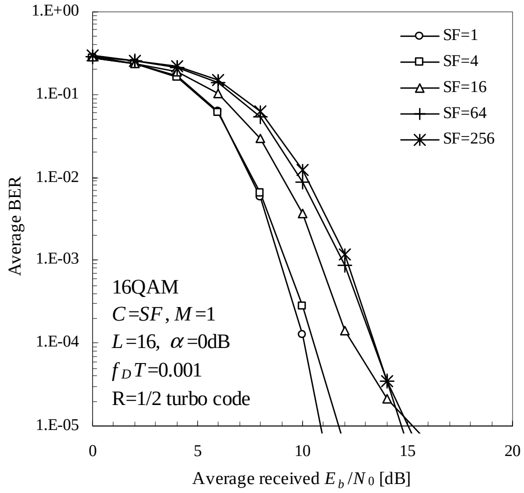


(c) 64QAM modulation

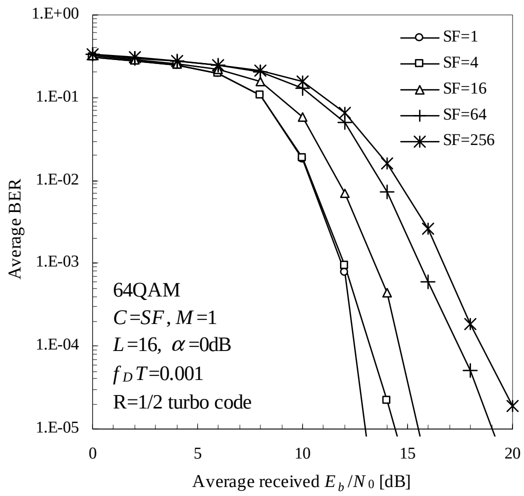
Fig. 2. Uncoded BER performance for different modulation level with *SF* as a parameter.



(a) QPSK modulation



(b) 16QAM modulation



(c) 64QAM modulation

Fig. 3. Coded BER performance for different modulation level with *SF* as a parameter.

are closer and even a small destruction in orthogonality results in a decision error. In the larger E_b/N_0 regions, E_b/N_0>12dB and 20dB for 16QAM and 64QAM respectively, the BER is better for higher *SF*. For a BER=10^{-3} or 10^{-4}, larger *SF* is seen to provide a better BER. Hence, it can be said that for the uncoded case, multicode transmission with *SF*=N_c provides the best BER performance.

The scenario is completely different when channel coding is applied. The average BER with rate ½ turbo code is plotted in Figs. 3(a)~(c) for QPSK, 16QAM and 64QAM, respectively. The number of receive antennas *M*=1 is assumed. It is seen that in sharp contrast to the uncoded case, the BER dependence on *SF* is very different. With channel coding, there is a tradeoff between frequency diversity gain due to the spreading of symbols, coding gain due to better interleaving effect and orthogonality destruction. OFDM also avails from coding gain due to better frequency interleaving effect when turbo coding is applied. Each subcarrier carries a different symbol and experiences different fading resulting in a better interleaving effect. For multicode MC-CDMA, the equivalent channel gain is the same for *C* symbols. For QPSK, the average BER for *SF*=1 (OFDM) is almost the same as that for *SF*=N_c. It is seen that *SF*=16 has the worst BER. For 16QAM and 64QAM, the BER improves as *SF* decreases. It is seen that coding gain due to better interleaving is more desirable than frequency diversity gain due to spreading which also results in orthogonality destruction. For 16QAM (64QAM), the average E_b/N_0 for a BER=10^{-4} is 3dB (6dB) less for *SF*=1 compared to *SF*=256.

Figure 4 plots the coded average BER as a function of the decay factor α of the exponential delay profile of the channel for 64QAM when *M*=1. The channel is highly frequency selective for α=0dB and approaches a single path channel as $\alpha \to \infty$. It can be observed from the figure that as the frequency-selectivity of the channel decreases, the performance degrades for all *SF* due to the decrease in the frequency diversity effect. For very high α, the performance is almost independent of *SF*; however for lower α, smaller *SF* has low BER. Hence, it can be said that irrespective of the channel's frequency-selectivity, lower *SF* provides a better BER performance.

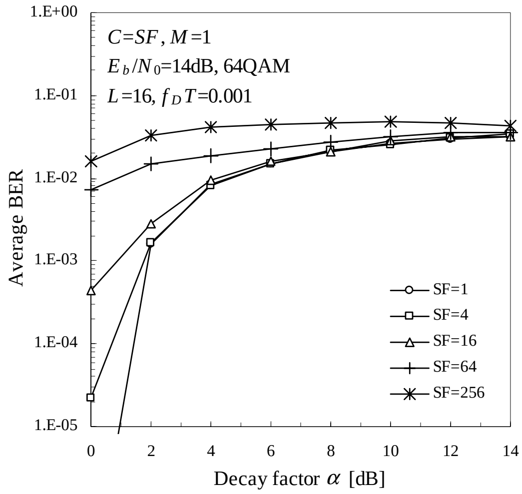


Fig. 4. Coded BER for 64QAM as a function of the decay factor α.

The coded average BER with 2-antenna receive diversity and turbo coding is plotted in Fig. 5. It is seen that even with receive antenna diversity, for QPSK, *SF*=1 (OFDM) has the best performance followed by that of *SF*=256. *SF*=16 is seen to have the worst BER performance. However, for 16QAM and 64QAM, the lower the *SF*, the better is the BER performance.

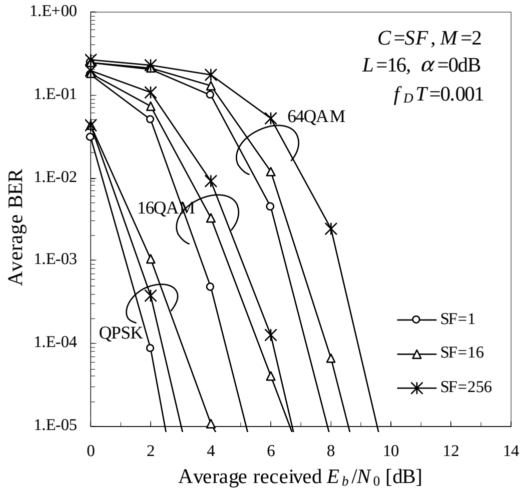


Fig. 5. Coded BER performance with antenna diversity (*M*=2).

4. Conclusion

The BER performance of MC-CDMA with high level modulation was evaluated by computer simulations. It was found that without channel coding, BER is better for higher *SF* due to higher frequency diversity gain for all modulation levels. However, with turbo coding, the BER is better for lower *SF*. The BER performance of OFDM is better than that of MC-CDMA.

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