Performance Comparison of Turbo-coded DS-CDMA, MC-CDMA and OFDM with Frequency-domain Equalization and Higher-level Modulation

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Abstract— **For high-speed data communications, channel coding and high-level modulation will be inevitable. In this paper, we compare the turbo coded performances of DS-CDMA and MC-CDMA which are the major contenders for next generation wireless signaling technique. Minimum mean square frequency-domain equalization (MMSE-FDE) is assumed for both DS-CDMA and MC-CDMA. The log-likelihood ratio (LLR) computation is used to generate the soft decision value needed for turbo decoding. It is found that the DS-CDMA performance is the same for all spreading factor (*SF*) and equivalent to a fully spread MC-CDMA for all modulation levels and coding rates. For an uncoded system, DS-CDMA is better than MC-CDMA for smaller *SF* due to a larger frequency diversity gain. However, with turbo coding, MC-CDMA with smaller *SF* provides better performance due to larger coding gain owing to better frequency interleaving and severe orthogonality destruction for larger *SF* and DS-CDMA wherein a symbol is spread over the entire bandwidth.**

Keywords- ***DS-CDMA, MC-CDMA, MMSE-FDE, MQAM, turbo coding***

I. INTRODUCTION

Direct sequence code division multiple access (DS-CDMA) and multi-carrier code division multiple access (MC-CDMA), are the major contenders for next generation wireless communications systems. For high-speed data communications, the use of high-level modulation like 16 quadrature amplitude modulation (16QAM) and 64QAM is inevitable. In DS-CDMA, the data-modulated symbol to be transmitted is spread using an orthogonal spreading sequence defined in the time-domain. On the other hand, in MC-CDMA [1], frequency-domain spreading over a number of subcarriers is used. OFDM is taken as a special case of MC-CDMA with a spreading factor *SF*=1. DS-CDMA with minimum mean square frequency-domain equalization (MMSE-FDE) [2] gives a performance comparable to that of MC-CDMA with MMSE-FDE in a frequency-selective fading channel. However, for high speed data transmissions, M-ary QAM (MQAM) is necessary. In addition, some form of error control is needed to improve the transmission performance. Turbo coding has been found to provide strong error correction capabilities. In [2], higher level modulation and channel coding has not been considered. In this paper, we compare the DS-CDMA and MC-CDMA performance with MQAM and turbo coding in a frequency-selective channel.

The remainder of the paper is organized as flows. Section II describes the DS-CDMA and MC-CDMA transmission system model. Simulation results and discussions are presented in Sect. III. Section IV concludes the paper.

II. DS-CDMA AND MC-CDMA

A. DS-CDMA

The unified transmission system model for DS-CDMA and MC-CDMA, both with MMSE-FDE, is shown in Fig. 1. For DS-CDMA, the IFFT block in the transmitter is not present. The binary information sequence is turbo coded, bit-interleaved and transformed into a data-modulated symbol sequence with symbol length T_s. The symbol sequence is serial-to-parallel (S/P) converted to C streams $\{x_c(n), c=0\sim C-1\}$ and after each stream is spread with different orthogonal spreading code $\{c_{oc,c}(t), c=0\sim C-1, t=0\sim SF-1\}$ with spreading factor SF, they are code-multiplexed and further multiplied by a common scrambling sequence $\{c_{scr}(t)\}$. (C is called the code multiplexing order.) In this paper, chip-spaced discrete-time representation of signals is used. The resulting sequence is expressed using the low-pass equivalent representation as

$$s(t)=\sqrt{2P/SF}\sum_{c=0}^{C-1}x_c\left(\lfloor t/SF\rfloor\right)c_{oc,c}(t \bmod SF)c_{scr}(t) \qquad (1)$$

where P represents the transmit power per spreading code and $\lfloor a\rfloor$ denotes the largest integer smaller than or equal to a. The code multiplexed chip sequence is transmitted after the insertion of N_g sample guard interval (GI) for every block of N_c chips. GI is required in DS-CDMA with MMSE-FDE [2] to maintain the periodicity within the FFT window at the receiver.

For simplicity, without loss of generality, we assume the reception of a block of N_c+N_g chips. At the receiver, M antenna diversity reception is assumed. N_c-point FFT and MMSE-FDE is applied to the signal received by each antenna

$\{\tilde{r}_m(t); t=0\sim N_g+N_c-1\}$ after the removal of GI. The equalized signals from M antennas are combined and IFFT is performed followed by multicode despreading to obtain [3]

$$\begin{aligned}\hat{x}_c(n) &= \sum_{t=nSF}^{(n+1)SF-1}\hat{s}(t)\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^* \\ &= \sqrt{\frac{2P}{SF}}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}(k)\right)x_c(n)+\mu_{ICI}^{ds}(n)+\mu_{AWGN}^{ds}(n)\end{aligned} \tag{2}$$

for c=0~C-1 and n=0~N_c/SF–1, where $\hat{s}(t)$ is the time-domain signal obtained after IFFT and $\tilde{H}(k)=\sum_{m=0}^{M-1}H_m(k)w_m(k)$; $H_m(k)$ is the mth antenna's channel gain seen at the kth frequency and $w_m(k)$ is the corresponding FDE weight given by

$$w_m(k)=\frac{H_m^*(k)}{\sum_{m=0}^{M-1}|H_m(k)|^2+[(C/SF)(PT_s/N_0)]^{-1}}. \tag{3}$$

In Eq. (2), the first term represents the desired data symbol component and the second and third terms, $\mu_{ICI}^{ds}(n)$ and $\mu_{AWGN}^{ds}(n)$, are the inter-chip interference (ICI) and the noise due to AWGN, respectively, given by

$$\begin{cases}\mu_{ICI}^{ds}(n)=\dfrac{1}{SF}\displaystyle\sum_{t=nSF}^{(n+1)SF-1}\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^* \\ \qquad\times\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\tilde{H}(k)\left[\sum_{\substack{\tau=0\\ \neq t}}^{N_c-1}s(\tau)\exp\left(j2\pi k\frac{t-\tau}{N_c}\right)\right] \\ \mu_{AWGN}^{ds}(n)=\dfrac{1}{SF}\displaystyle\sum_{t=nSF}^{(n+1)SF-1}\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^*\tilde{\eta}^{ds}(t)\end{cases}, \tag{4}$$

where $\tilde{\eta}^{ds}(t)$ is the noise sample at time t due to the AWGN. It can be understood from Eq. (2) that the equivalent channel gain for all the symbols within an FFT block is $\hat{H}(n)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}(k)$ and the frequency diversity gain is a not a function of SF. $\{\hat{x}_c(n); c=0\sim C-1\}$ are parallel-to-serial (P/S) converted for data demodulation. Then, soft decision values for turbo decoding are generated using the log-likelihood (LLR) approximation [4], given by

$$L(b)=\frac{\left|\hat{x}_c(n)-\sqrt{\frac{2P}{SF}}\hat{H}(n)\hat{s}_0\right|^2}{2\sigma^2}-\frac{\left|\hat{x}_c(n)-\sqrt{\frac{2P}{SF}}\hat{H}(n)\hat{s}_1\right|^2}{2\sigma^2} \tag{5}$$

for the bth bit in the nth symbol, b=0~B-1. B is the number of bits in a symbol and B=2, 4 and 6 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 $\hat{x}_c(n)$ is minimum. $2\sigma^2$ is the Gaussian approximated ICI plus noise variance, given by [3]

$$\sigma^2=\frac{1}{SF}\frac{N_0}{T_s}\left[\begin{array}{l}\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}|w(k)|^2 \\ +\left(\dfrac{C}{SF}\dfrac{PT_s}{N_0}\right)\left\{\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}|\tilde{H}(k)|^2-\left|\dfrac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}(k)\right|^2\right\}\end{array}\right]. \tag{6}$$

The LLR values are computed for c=0~C-1 and for the B bits in the symbol. Turbo decoding is performed using these LLR values as soft input after deinterleaving and depuncturing. DS-CDMA with SF=C=1 is in fact the single carrier system [5].

B. MC-CDMA

The MC-CDMA transmission system model is similar to that of DS-CDMA except that, in MC-CDMA, the multicode chip sequence is S/P-converted and IFFT is performed at the transmitter. The low-pass equivalent of the code multiplexed signal transmitted after N_c-point IFFT can be written as

$$\begin{aligned}s(t) &= \sqrt{\frac{2P}{SF}}\sum_{k=0}^{N_c-1}\sum_{c=0}^{C-1}x_c\left(\left\lfloor\frac{k}{SF}\right\rfloor\right)c_{oc}^c(k \bmod SF) \\ &\quad\times c_{scr}(k)\exp\left(j2\pi k\frac{t}{N_c}\right)\end{aligned} \tag{7}$$

where t represents the sample position within the signaling interval $0\le t<N_c$ and P is the transmit power per spreading code. The MC-CDMA signal is transmitted after the insertion of an N_g sample GI.

At the receiver, FFT is performed to get the frequency-domain signal $\{R_m(k)\}$ and MMSE-FDE is performed using the weight as in Eq. (3). The IFFT block at the receiver in Fig. 1 should be omitted. Frequency-domain despreading is applied to obtain

$$\begin{aligned}x_c(n) &= \frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\sum_{m=0}^{M-1}R_m(k)w_m(k)\{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^* \\ &= \sqrt{\frac{2P}{SF}}\left(\frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)\right)d_c(n)+\mu_{ICI}^{mc}(n)+\mu_{AWGN}^{mc}(n)\end{aligned} \tag{8}$$

for c=0~C-1 and n=0~N_c/SF-1. The first term represents the desired signal component and the second and third terms are the ICI and noise due to AWGN, respectively, given by

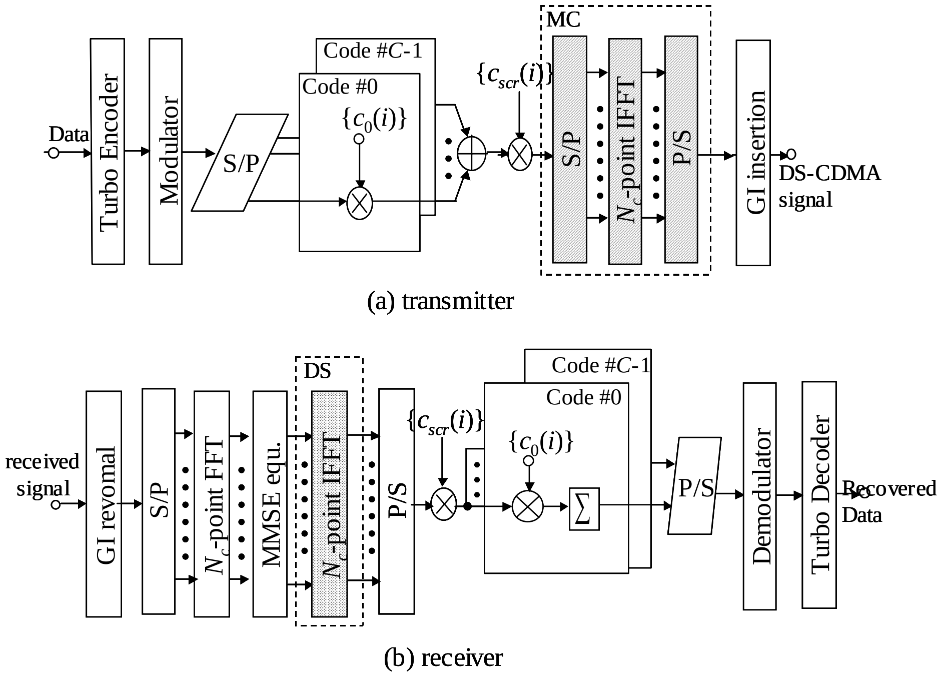

Fig. 1 Transmission system model

$$\begin{cases} \mu_{ICI}^{mc}(n) = \dfrac{1}{SF}\sqrt{\dfrac{2P}{SF}} \displaystyle\sum_{k=nSF}^{(n+1)SF-1} \tilde{H}(k)\{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^{*} \\ \qquad\qquad \times \displaystyle\sum_{\substack{c'=0 \\ \neq c}}^{C-1} x_{c'}(k)\{c_{oc,c'}(k \bmod SF)c_{scr}(k)\}, \quad (9) \\ \mu_{AWGN}^{mc}(n) = \dfrac{1}{SF} \displaystyle\sum_{k=nSF}^{(n+1)SF-1} \{c_{oc,c}(k \bmod SF)c_{scr}(k)\}^{*}\tilde{\eta}^{mc}(k) \end{cases}$$

where $\tilde{\eta}^{mc}(k)$ is the noise sample at subcarrier k due to the AWGN. Unlike DS-CDMA, the equivalent channel gain for each symbol is $\hat{H}(n) = \frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1}\tilde{H}(k)$, and the frequency diversity gain is a function of *SF*. After P/S conversion, the sequence $\{\hat{x}_c(n); c = 0 \sim C-1 \text{ and } n = 0 \sim N_c/SF-1\}$ is soft demodulated using the LLR as for DS-CDMA and turbo-decoded after deinterleaving and depuncturing. MC-CDMA system with *SF*=*C*=1 is an OFDM system.

III. Simulation Results

We assume a frequency-selective Rayleigh fading channel having a 16-path uniform power delay profile with a time-delay spacing of $1T_c$ between adjacent paths and a normalized maximum Doppler frequency $f_D T_{blk}$ of 0.001, where $T_{blk}=T_c(N_c+N_g)$; T_c is the FFT sampling interval (equal to the chip duration) and N_c is the number of subcarriers (equal to the number of FFT points) for MC-CDMA (DS-CDMA). In the simulation, N_c=256 and N_g=32 are assumed. We assume that *SF*=*C* for MC-CDMA and DS-CDMA so that the data rate is same as OFDM for all *SF*. A rate ½ turbo code [6] with a constraint length of 4 and decoding with 8 iterations is assumed. The data sequence length is taken to be 1024 bits. A 32x64-bit block interleaver is assumed.

The uncoded performance is evaluated first and then the effect of using channel coding is evaluated. Figure 2 plots the BER performance of DS-CDMA and MC-CDMA as a function of the average received signal energy per bit-to-noise power spectral density ratio (E_b/N_0) for different *SF* when *M*=1 (no antenna diversity) and the data modulation is 16QAM. $E_b=PT_s(1+N_g/N_c)/B$ and includes the power loss due to GI insertion. It is seen that the performance is almost independent of *SF* as was shown in Sect. II. For DS-CDMA with MMSE-FDE, the frequency diversity effect is not a function of *SF* as each symbol is spread over the entire bandwidth and the equalization is performed in frequency domain. Full diversity gain is attained for all *SF*. The interference depends on the *C*/*SF* ratio and since *C*/*SF*=1, the interference is also the same for all *SF*. Hence the performance is the same for all *SF*. For MC-CDMA, on the other hand, the BER performance depends on the spreading factor *SF*. Higher *SF* has a higher frequency diversity effect, but at the same time, the orthogonality destruction is severer in a frequency-selective channel. The frequency band over which a symbol is spread is wider for larger *SF* and the channel gain is no more constant over the band resulting in orthogonality destruction among the multiplexed codes. MMSE-FDE that provides a good trade-off between noise enhancement and orthogonality restoration is applied. The BER performance curve with MC-CDMA for $SF=N_c$ coincides with the DS-CDMA curve.

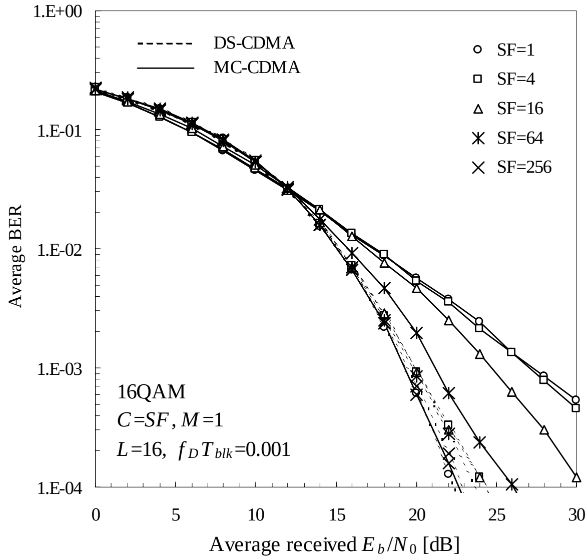

Fig. 2 Uncoded BER performances of DS-CDMA and MC-CDMA for 16QAM.

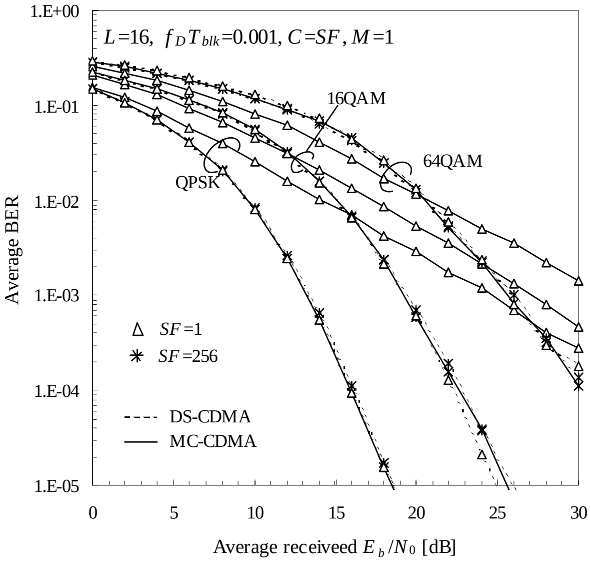

Fig. 3 Uncoded BER performances of DS-CDMA and MC-CDMA for QPSK, 16QAM and 64QAM.

Figure 3 compares the DS-CDMA and MC-CDMA performance for QPSK, 16QAM and 64QAM. Only the extreme cases, *SF*=256 and *SF*=1 are considered. DS-CDMA with *SF*=1 is the non-spread single carrier system [5]. The DS-CDMA performance does not depend on *SF* and hence the *SF*=1 and *SF*=256 curves coincide for all modulation levels. The MC-CDMA curve with $SF=N_c$, which avails from full frequency diversity gain, also coincide with the corresponding DS-CDMA curves. Because of higher frequency diversity, the MC-CDMA with *SF*=256 and DS-CDMA performance are better than that of MC-CDMA with *SF*=1 (OFDM). However, for 16QAM and 64QAM, in the lower average received E_b/N_0 regions (noise dominant region), the MC-CDMA (*SF*=256) and DS-CDMA performance are worse due to the short Euclidean distance between the signal points and severe orthogonality destruction which results in more decision errors. This causes the result to be different when channel coding is used.

Figure 4 compares the coded BER performance for DS-CDMA and MC-CDMA as a function of E_b/N_0 for QPSK, 16QAM and 64QAM. As for Fig. 3, only the extreme cases are plotted. *C*=*SF* is assumed to always maintain the same data rate as OFDM. Even with rate ½ turbo coding, the DS-CDMA performance is the same for all *SF*. However, for MC-CDMA, the performance trend is opposite to that of the uncoded case. The smaller the *SF*, the better is the BER [7]. With channel coding, there is a trade-off among frequency diversity gain due to spreading, coding gain due to better interleaving effect and orthogonality destruction. OFDM (MC-CDMA with *SF*=1) 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 with *SF*=256, the equivalent channel gain is the same for *C* symbols. Therefore, the interleaving becomes less effective. In addition, the orthogonality destruction is worse as *SF* increases. As for the uncoded case, DS-CDMA curves coincide the MC-CDMA curve with $SF=N_c$=256. With channel coding, OFDM provides almost similar performance to DS-CDMA and MC-CDMA for QPSK. But, for 16QAM and 64QAM, the OFDM performance is better than that of MC-CDMA and DS-CDMA.

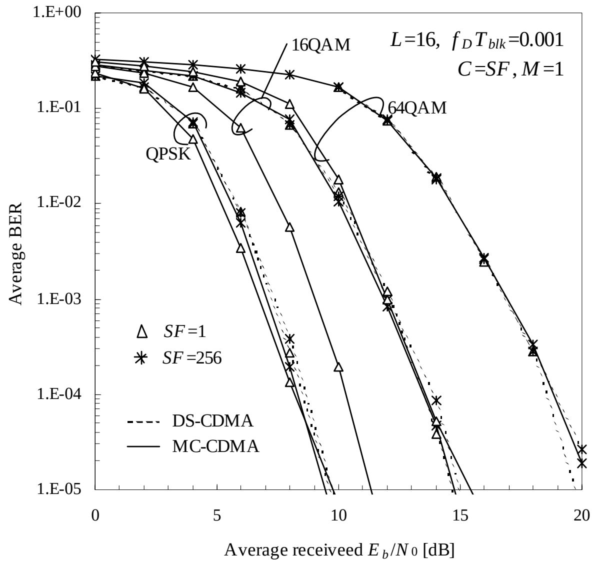

Fig. 4 Coded BER performances of DS-CDMA and MC-CDMA.

Figure 5 plots the required average received E_b/N_0 for a BER=10^{-4} as a function of *SF* with the coding rate *R* as a parameter for 16QAM when *M*=1. For all coding rate, the DS-CDMA performance is independent of *SF* and equivalent to the MC-CDMA performance with $SF=N_c$. The MC-CDMA performance is sensitive to *SF*. It can be observed from Fig. 5 that for MC-CDMA when *R*=½, the required average E_b/N_0 is the lowest for *SF*=1 (OFDM). As the coding rate increases, the coding gain decreases. Coding improves the performance for all *SF* at the cost of redundancy, however the improvement is the largest for OFDM; the required average E_b/N_0 for OFDM decreases by about 16dB even with a small amount of redundancy (R=9/10). Higher *SF* benefits from frequency diversity due to spreading. However, higher coding gain due to better interleaving and less orthogonality destruction accounts for the lack of frequency diversity gain for smaller *SF*. Therefore, in MC-CDMA, as *SF* increases, the required E_b/N_0 increases but it starts to decrease beyond a certain *SF*. This is because the frequency diversity gain becomes stronger and offsets the adverse effect of orthogonality destruction.

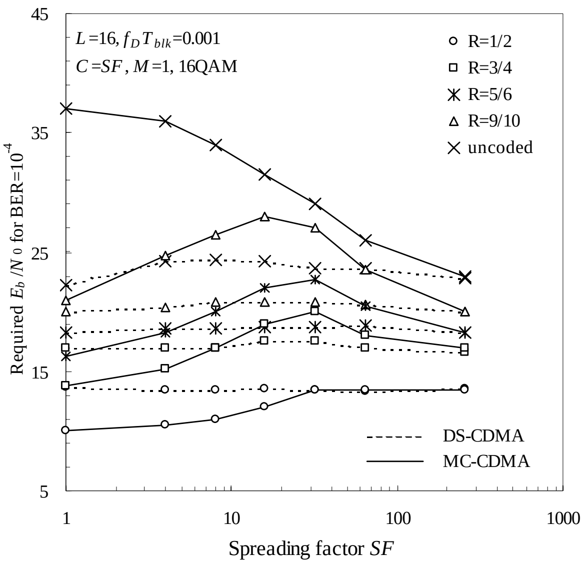

Fig. 5 Required average E_b/N_0 for a BER=10^{-4}.

The performance comparison in the presence of transmit and receive antenna diversity is plotted in Fig. 6. Space time transmit diversity (STTD) [8] with two transmit antennas is employed. The MMSE-FDE weight is modified as in [9]. Two antenna receive diversity is also used in addition to STTD. It can be observed that even with antenna diversity, the DS-CDMA performance is the same as that of MC-CDMA with *SF*=256 and that the OFDM performance is better for 16QAM and 64QAM. However, due to antenna diversity in addition to frequency diversity, the difference in the performance is very less. The required average E_b/N_0 for a BER=10^{-4} is only about 0.5dB more for MC-CDMA and DS-CDMA both with *SF*=256 than OFDM.

IV. CONCLUSION

The BER performance comparison of DS-CDMA and MC-CDMA was presented for various modulation levels (QPSK, 16QAM and 64QAM). It was found that for an uncoded system, DS-CDMA (any *SF*) and MC-CDMA ($SF=N_c$) provides the best performance due to a larger frequency diversity gain. However, with turbo coding, DS-CDMA and MC-CDMA provide similar performance for QPSK modulation, but for 16QAM and 64QAM, MC-CDMA with *SF*=1 (OFDM) provides better performance due to severe orthogonality destruction in DS-CDMA and MC-CDMA. With antenna diversity the difference in the performance reduces; MC-CDMA performance is almost the same as DS-CDMA for all *SF*.

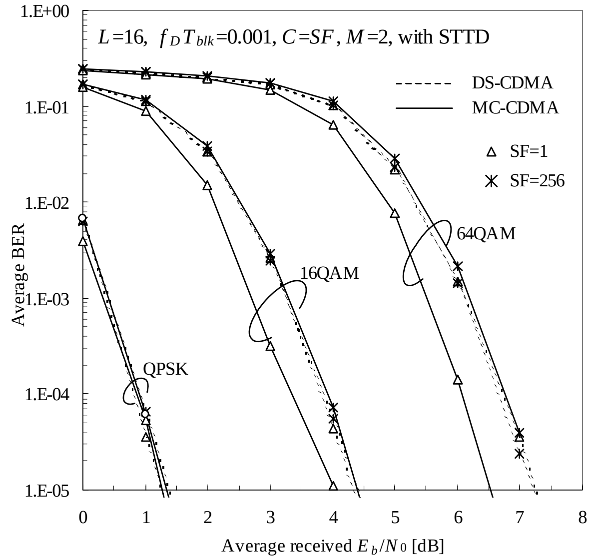

Fig. 6 Coded BER with STTD and antenna receive diversity.

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