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Impact of Spreading Factor on Turbo-coded Multi-code MC-CDMA using ICI cancellation

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***Abstract*-Multi-carrier code division multiple access (MC-CDMA) is one of promising broadband wireless access techniques. Frequency-domain equalization (FDE) based on the minimum mean square error (MMSE) criterion can take advantage of the channel frequency-selectivity and improve the average bit error rate (BER) performance of single-code MC-CDMA due to frequency-diversity gain. However, as the code multiplexing order is increased so as to increase the data rate without bandwidth expansion, the presence of residual inter-code interference (ICI) degrades the transmission performance. Recently, we proposed a frequency-domain adaptive interference cancellation (FDAIC) technique to mitigate the residual ICI and showed that the full code multiplexed MC-CDMA with FDAIC achieves better performance than orthogonal frequency division multiplexing (OFDM). However, the impact of spreading factor was not discussed. In this paper, we evaluate, by computer simulation, the average BER and throughput performances of turbo-coded MC-CDMA with FDAIC for different values of spreading factor, and show that the full-code multiplexed MC-CDMA with FDAIC using the full spreading factor (equal to the number of subcarriers) can provide almost the same or better transmission performance than OFDM.**

Keywords: MC-CDMA, code-multiplexing, interference cancellation, turbo-coding

I. INTRODUCTION

Multi-carrier code division multiple access (MC-CDMA) can take advantage of the channel frequency-selectivity to achieve the frequency-diversity gain and is considered as one of promising broadband wireless access techniques [1-3]. MC-CDMA has high flexibility in variable rate data transmissions by code-multiplexing. In a broadband frequency-selective channel, the orthogonality property among different orthogonal spreading codes used in the code-multiplexing is distorted due to the strong channel frequency-selectivity; thereby producing the inter-code interference (ICI). Frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion can suppress the ICI while mitigating the noise enhancement and significantly improve the bit error rate (BER) performance of single-code MC-CDMA [3]. However, the distorted signal cannot be completely equalized by MMSE-FDE and the residual ICI after MMSE-FDE degrades the achievable BER performance as the code-multiplexing order increases. Recently, we have shown [4-5] that the use of frequency-domain adaptive interference cancellation (FDAIC) can mitigate the residual ICI and hence, sufficiently improve the BER performance of multi-code MC-CDMA; if the residual ICI is perfectly removed, the full code-multiplexed MC-CDMA can achieve a better BER performance than orthogonal frequency division multiplexing (OFDM) [6-7]. However, the impact of spreading factor has not been discussed (in [4-5], the maximum spreading factor equal to the number of subcarriers is assumed). In this paper, we evaluate, by computer simulation, the average BER and throughput performances of turbo-coded MC-CDMA with FDAIC for different values of spreading factor and discuss the impact of spreading factor.

The remainder of this paper is organized as follows. Sect. II introduces the transmission system model of turbo-coded MC-CDMA using FDAIC. In Sect. III, the achievable average BER and throughput performances of turbo-coded full-code multiplexed MC-CDMA with FDAIC are presented and the impact of spreading factor is discussed. Sect. IV offers some conclusions.

II. TRANSMISSION SYSTEM MODEL

Figure 1 illustrates the transmitter/receiver structure of turbo-coded MC-CDMA with FDAIC. The full code-multiplexing is assumed to achieve the same data rate as OFDM.

At the transmitter, after turbo coding [8], puncturing, and channel interleaving, the turbo-coded bit sequence is transformed into a data-modulated symbol sequence and the symbol sequence is serial-to-parallel (S/P) converted to SF symbol streams $\{d_c(n);\ n=0\sim N_c/SF-1\}$ with $E[|d_c(n)|^2]=1$, $c=0\sim(SF-1)$, where N_c is the fast Fourier transform (FFT) block size and SF is the spreading factor. SF data symbol sequences $d_c(n)$, $c=0\sim(SF-1)$, to be transmitted are respectively spread by orthogonal spreading codes $\{c_c(t);\ t=0\sim(SF-1)\}$ with $|c_c(t)|=1$, $c=0\sim(SF-1)$, to obtain the full-code multiplexed chip sequence and further multiplied with a scrambling sequence $c_{scr}(t)$. The resulting chip sequence is divided into a sequence of N_c-chip blocks. N_c-point IFFT is applied to each chip block to generate the MC-CDMA signal with N_c subcarriers. After inserting the guard interval (GI), the MC-CDMA signal is transmitted.

At the receiver, after removing the GI, N_c-point FFT is applied to decompose the received signal into N_c subcarrier components and FDAIC is carried out before data-demodulation (the operation principle of FDAIC is described later).

A. *Transmitted signal*

The MC-CDMA signal $s(t)$, $t=0\sim(N_c-1)$, can be expressed using the equivalent low-pass representation as

$$s(t)=\sqrt{\frac{2E_s}{T_cSF}}\frac{1}{\sqrt{N_c}}\sum_{k=0}^{N_c-1}S(k)\exp\left(j2\pi t\frac{k}{N_c}\right)\ ,\qquad (1)$$

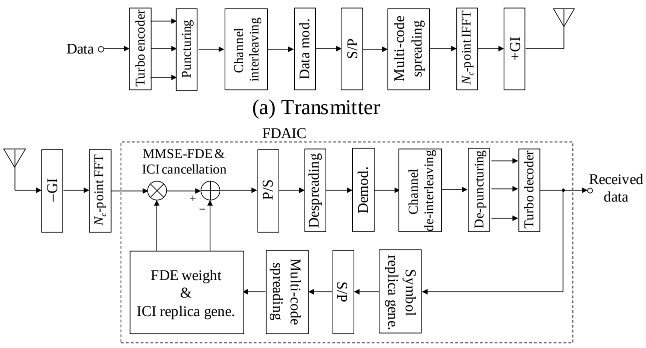


Fig.1 Transmitter/receiver structure.

where E_s and T_c denote the data-symbol energy and FFT/IFFT sampling period, respectively. $S(k)$ is the k-th (k=0~(N_c−1)) subcarrier component, given as

$$S(k)=\sum_{c=0}^{SF-1} d_c\left(\lfloor k/SF\rfloor\right)c_c(k \bmod SF)c_{scr}(k) \quad , \tag{2}$$

where $\lfloor x \rfloor$ is the largest integer smaller than or equal to x.

B. Received signal

The MC-CDMA signal $s(t)$ is transmitted over a frequency-selective fading channel. We assume a sample-spaced L-path frequency-selective block fading channel. The complex-valued path gain and time delay of the l-th propagation path are denoted by h_l and τ_l, l=0~(L−1), respectively. The channel impulse response $h(\tau)$ is expressed as [9-11]

$$h(\tau)=\sum_{l=0}^{L-1} h_l \delta(\tau-\tau_l) \tag{3}$$

with $E[|\sum_{l=0}^{L-1} h_l|^2]=1$.

The GI-removed received MC-CDMA signal $r(t)$ can be expressed as

$$r(t)=\sum_{l=0}^{L-1} h_l s(t-\tau_l)+\eta(t) \quad , t=0\sim(N_c-1), \tag{4}$$

where $\eta(t)$ is the zero-mean additive white Gaussian noise (AWGN) with variance $2N_0/T_c$ with N_0 being the single-sided power spectrum density.

N_c-point FFT is applied to decompose the received signal $r(t)$ into N_c subcarrier components $R(k)$ as

$$\begin{aligned} R(k)&=\frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1} r(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \\ &=\sqrt{\frac{2E_s}{SF\cdot T_c}}H(k)S(k)+\Pi(k), \end{aligned} \quad , \tag{5}$$

with

$$\begin{cases} H(k)=\sum_{l=0}^{L-1} h_l \exp\left(-j2\pi k\frac{\tau_l}{N_c}\right) \\ \Pi(k)=\frac{1}{\sqrt{N_c}}\sum_{t=0}^{N_c-1}\eta(t)\exp\left(-j2\pi k\frac{t}{N_c}\right) \end{cases} . \tag{6}$$

C. FDAIC

In FDAIC, a series of MMSE-FDE, ICI cancellation, despreading, and turbo decoding is repeated I times. Below, we describe the i-th stage of iteration, i=0~(I−1).

The i-th stage iteration is expressed as [4]

$$\tilde{R}_i(k)=w_i(k)R(k)-M_i(k) \quad , \tag{7}$$

where $w_i(k)$ and $M_i(k)$ denote the MMSE weight and the residual ICI replica, respectively. $w_i(k)$ is given by [4]

$$w_i(k)=\frac{H^*(k)}{|H(k)|^2\sum_{c=0}^{SF-1}\rho_{c,i-1}\left(\lfloor k/SF\rfloor\right)+\left(\frac{1}{SF}\frac{E_s}{N_0}\right)^{-1}} , \tag{8}$$

with

$$\rho_{c,i-1}(n)=E[|d_c(n)|^2]-|\tilde{d}_{c,i-1}(n)|^2 \quad , \tag{9}$$

where $\rho_{c,i-1}(n)$ is an interference coefficient with $\rho_{c,-1}(n)$=0. $E[|d_c(n)|^2]$ is the expectation of the data symbol for the given received signal and $\tilde{d}_{c,i-1}(n)$ is the soft symbol replica generated using the tentative decision results of the (i−1)-th iteration. $E[|d_c(n)|^2]$ and $\tilde{d}_{lc,i-1}(n)$ are given by [4]

$$\begin{aligned} E[|d_c(n)|^2]&=\sum_{d\in D}|d|^2\prod_{b_{c,x}(n)\in d}p(b_{c,x}(n)) \\ &=\begin{cases} 1, \quad \text{for QPSK} \\ \frac{4}{10}\tanh\left(\frac{\lambda_{c,i-1,1}(n)}{2}\right)+\frac{4}{10}\tanh\left(\frac{\lambda_{c,i-1,3}(n)}{2}\right)+1, \text{ for 16QAM} \end{cases} \end{aligned} \tag{10}$$

$$\begin{aligned} \tilde{d}_{c,i-1}&=\sum_{d\in D} d\prod_{b_{c,x}(n)\in d}p(b_{c,x}(n)) \\ &=\begin{cases} \frac{1}{\sqrt{2}}\tanh\left(\frac{\lambda_{c,i-1,0}(n)}{2}\right)+j\frac{1}{\sqrt{2}}\tanh\left(\frac{\lambda_{c,i-1,1}(n)}{2}\right) \quad \text{for QPSK} \\ \frac{1}{\sqrt{10}}\tanh\left(\frac{\lambda_{c,i-1,0}(n)}{2}\right)\left\{2+\tanh\left(\frac{\lambda_{c,i-1,1}(n)}{2}\right)\right\} \\ +j\frac{1}{\sqrt{10}}\tanh\left(\frac{\lambda_{c,i-1,2}(n)}{2}\right)\left\{2+\tanh\left(\frac{\lambda_{c,i-1,3}(n)}{2}\right)\right\} \text{ for 16QAM} , \end{cases} \end{aligned} \quad , \tag{11}$$

where d represents the candidate symbol in the symbol set D and $\lambda_{c,i-1,x}(n)$ is the i-th stage turbo decoder output LLR associated with the x-th bit $b_{c,x}(n)$ consisting of the n-th symbol $d_c(n)$, x=0~($\log_2 M$−1), for M-QAM data modulation. Assuming ideal data decision, the soft symbol replica $\tilde{d}_{c,i-1}(n)$ is given by $d_c(n)$.

The residual ICI replica $M_i(k)$ is given by [4]

$$M_i(k)=\sqrt{\frac{2E_s}{T_c SF}}\{w_i(k)H(k)-\hat{H}_i(\lfloor k/SF\rfloor)\}\tilde{S}_{i-1}(k), \tag{12}$$

where

$$\hat{H}_i(n) = \frac{1}{SF}\sum_{k=nSF}^{(n+1)SF-1} w_i(k)H(k) \tag{13}$$

is the equivalent channel gain after FDE. $\tilde{S}_{i-1}(k)$ is the transmitted symbol replica generated by replacing $d_c(n)$ by $\tilde{d}_{c,i-1}(n)$ in Eq. (2) as

$$\tilde{S}_{i-1}(k) = \sum_{c=0}^{SF-1}\tilde{d}_{c,i-1}(\lfloor k/SF \rfloor)c_c(k \bmod SF)c_{scr}(k) \tag{14}$$

with $\tilde{S}_{-1}(k) = 0$.

After the MMSE-FDE and ICI cancellation, the despreading and turbo-decoding (decoding is performed only once per FDAIC iteration) are carried out to obtain a sequence of log-likelihood ratios (LLRs) $\{\lambda_{c,i,x}(n)\}$. $E[|d_c(n)|^2]$, $\{\tilde{d}_{c,i}(n)\}$, and $\{\tilde{S}_i(k)\}$ are obtained by using $\{\lambda_{c,i,x}(n)\}$ to update the MMSE-FDE weight and the residual ICI replica for the $(i+1)$-th iteration.

Table I Simulation condition

Turbo coding	Encoder	Two (13,15) RSC encoders
	Decoder	Log-MAP decoding
	Coding rate	R=1/2, 3/4, 8/9
	Channel inter-leaver	Block
Transmitter	Modulation	QPSK, 16QAM
	No. of FFT points	N_c=256
	GI length	N_g=32
	Spreading sequence	Product of Walsh sequence and long PN sequence
	Spreading factor	SF=1, 4, 16, 64, 256
	Frequency-domain inter-leaver	Random
Channel	Fading	Frequency-selective block Rayleigh fading
	Power delay profile	L=16-path uniform power delay profile
	Time delay	$\tau_l=l$, l=0~15
Receiver	Channel estimation	Ideal
	No. of iterations	I=8

III. Computer Simulation

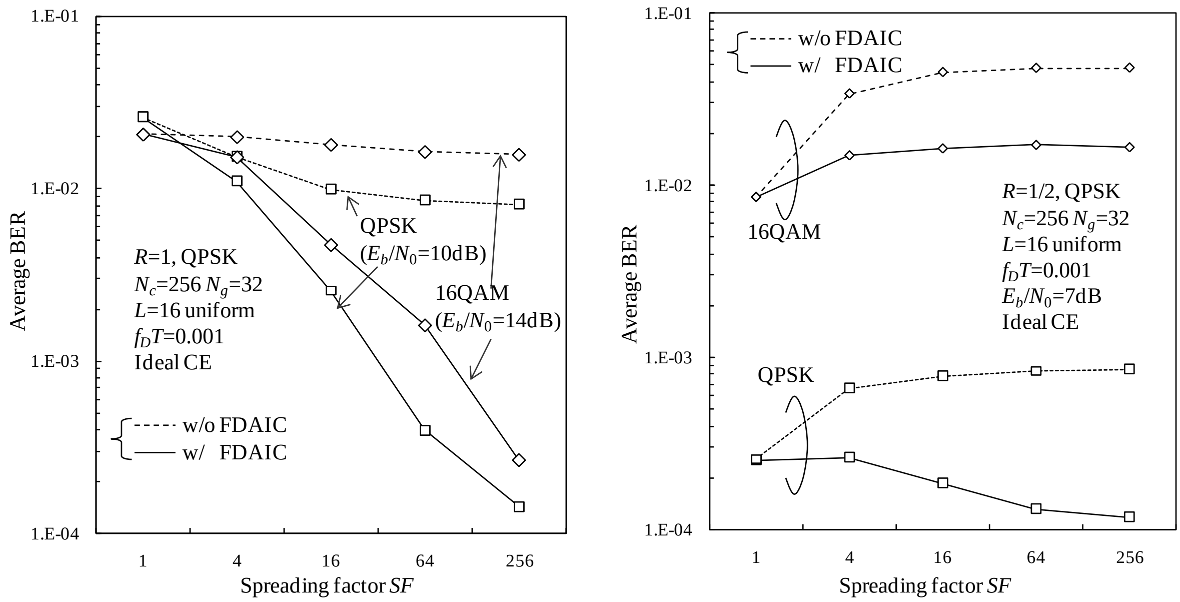
Table I summarizes the simulation condition. Since we are assuming the full code-multiplexing, multi-code MC-CDMA has the same data rate as OFDM. We assume QPSK (M=4) and 16QAM (M=16) data-modulation, an FFT block size of N_c=256, and a GI length of N_g=32. A turbo encoder with two (13,15) RSC encoders and a decoder with Log-MAP algorithm are used. The length of the coded bit sequence is 1024. Although frequency-domain interleaving is not introduced in Sect. II, it is used in the computer simulation to achieve larger frequency-diversity gain when $SF \ll N_c$. A sample-spaced L=16-path frequency-selective block Rayleigh fading channel with uniform power delay profile (i.e., $E[|h_l|^2]=1/L$ for all l) and the ideal channel estimation are assumed. The normalized maximum Doppler frequency is assumed to be f_DT=0.001 where $T=(N_c+N_g)T_c$ (which corresponds to a terminal moving speed of about 80 km/h for 100×10^6 symbol/sec and 5GHz carrier frequency). The number of iterations in FDAIC is assumed to be I=8, and only one turbo-decoding is performed per FDAIC iteration. For comparison, we also evaluate the transmission performances of OFDM and full-code multiplexed MC-CDMA without FDAIC (the number of turbo decoding iterations are 8 for the fare comparison).

D. Average BER performance

Figure 2 shows the average BER performance as a function of spreading factor SF for both of the uncoded case (R=1) and coded case (R=1/2). Even when frequency-domain interleaving is used, the full frequency-diversity gain cannot be achieved if the spreading factor SF is too small and the achievable diversity gain can be increased by increasing the value of SF until about, say, 16. For the uncoded case (R=1), by increasing the SF, the BER without FDAIC can be only slightly decreased because the residual ICI increases. However, when FDAIC is used, the residual ICI is sufficiently suppressed and therefore, the BER can be rapidly decreased by increasing the SF irrespectively of the modulation level. The reason for this is explained below. The accuracy of residual ICI replica generation for the ICI cancellation depends on the code-multiplexing order. It can be understood from Eq. (14) that the more accurate residual ICI replica can be generated due to better smoothing the negative impact of decision errors by increasing the code-multiplexing order.

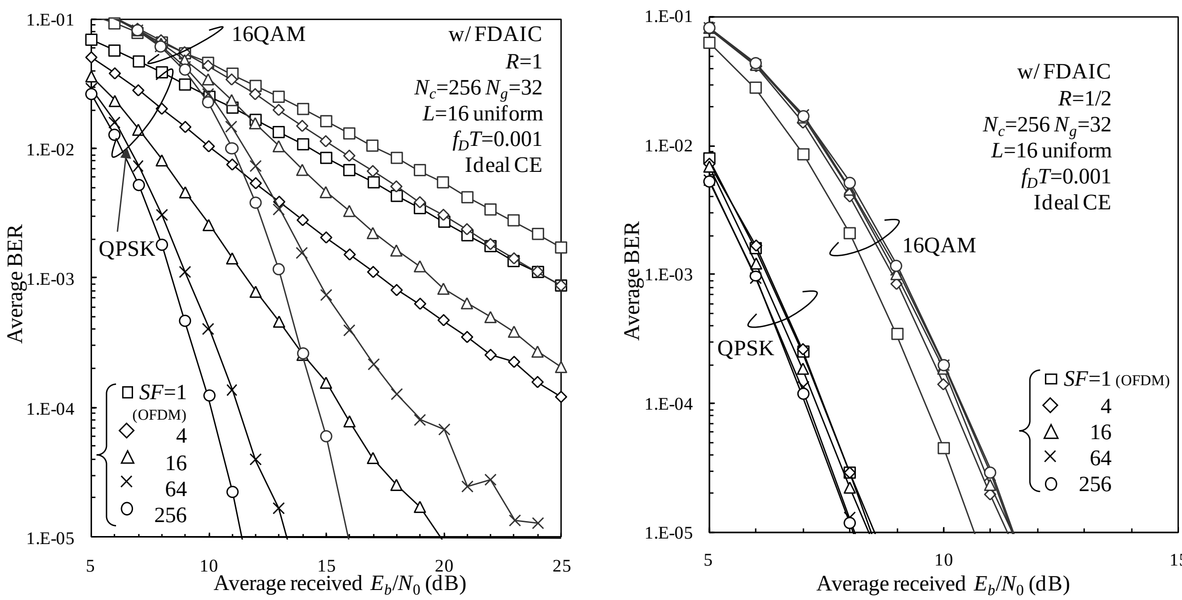
For the coded case (R=1/2), the BER without FDAIC increases as SF increases. This is because sufficiently larger coding gain is achieved than frequency-diversity gain, but the residual ICI gets larger as SF increases. However, in the case ofQPSK data modulation, the BER with FDAIC reduces as SF increases similar to the uncoded case. On the other hand, in the case of 16QAM data modulation, even when the FDAIC is used, the BER cannot be decreased by increasing the SF. This is because the impact of decision errors for 16QAM due to the residual ICI is stronger than for QPSK since the Euclidian distance between neighboring symbols is shorter for 16QAM, and therefore, the decision error is produced due to the residual ICI more likely than for QPSK. As a consequence, the BER performance of 16QAM only slightly improves.

Figure 3 shows the coded BER performance of full code-multiplexed MC-CDMA with FDAIC as a function of the average received bit energy per bit-to-noise spectrum density E_b/N_0 with SF as a parameter for QPSK and 16QAM when R=1 and 1/2. As understood from Fig. 3, when the coding rate R=1/2, since sufficiently larger coding gain is achieved than frequency-diversity gain, but the residual ICI gets larger as SF increases, the BER performance slightly increases as SF increases when 16QAM is used. However, when QPSK is used, the BER performance is almost insensitive to SF. On the other hand, in the uncoded case, the BER performance with FDAIC improves as SF increases. The reduction of the required E_b/N_0 for obtaining BER=10^{-2} is 8 (6.3) dB by increasing SF from 1 to 256 for QPSK (16QAM).



(a) R=1(uncoded) (b) R=1/2

Fig.2 Impact of spreading factor.



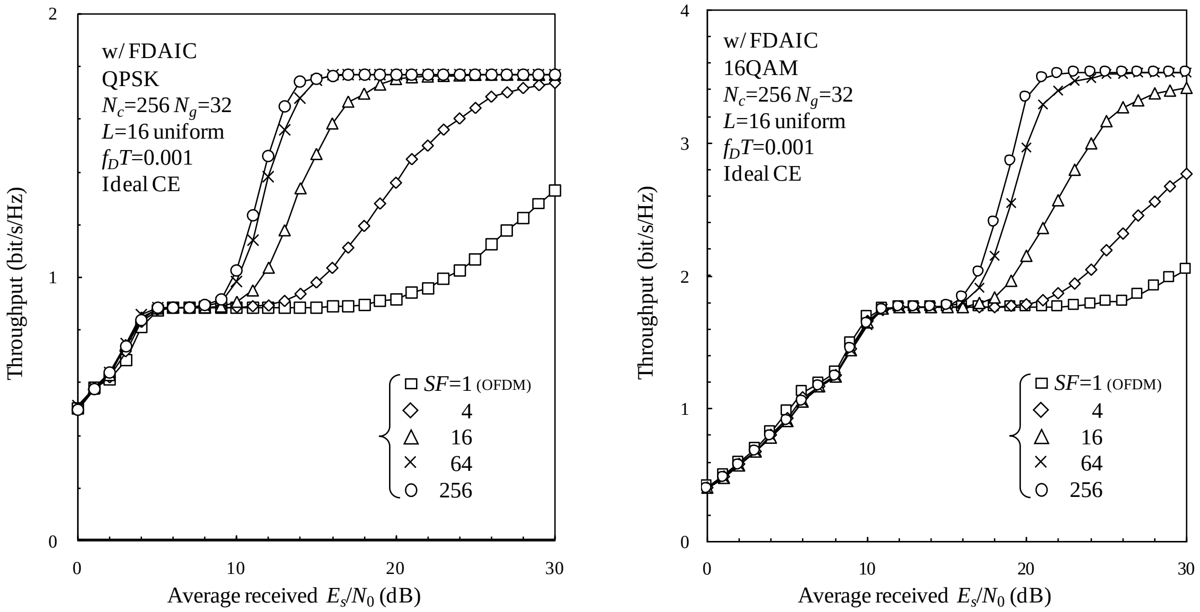
(a) R=1 (uncoded) (b) R=1/2

Fig.3 Average BER performance.

E. Throughput performance

The turbo-coded HARQ type-II with S-P2 [12-13] is considered as an example of HARQ using incremental redundancy (IR) strategy. The ideal error detection and no transmission error of the error information are assumed. In the HARQ type-II with S-P2, the uncoded packet is transmitted at initial transmission. After FDAIC (no turbo decoding is involved), the error detection is carried out. The parity check packet is transmitted if retransmission is requested, and then FDAIC with R=1/2-rate turbo-decoding is performed. If retransmission is requested again, another parity check packet is transmitted. As the number of retransmissions increase, the error correction capability gets stronger.

Figure 4 shows the throughput performance as a function of E_s/N_0 with SF as a parameter. Since the initial packet transmission is uncoded, no coding gain can be expected. Therefore, OFDM requires almost always the retransmission to get the coding gain even in the case of high E_s/N_0. The MC-CDMA with FDAIC can obtain the large frequency diversity gain and suppress the residual ICI with no parity check packet. Therefore, the throughout performance improves as SF increases in a high E_s/N_0(≥15dB) region. On the other hand, in a low E_s/N_0 region, almost the same throughput performance can be achieved irrespective of SF.



(a) QPSK (b) 16QAM

Fig.4 Throughput performance.

IV. CONCLUSION

In this paper, we evaluated, by computer simulation, the BER and throughout performances of turbo-coded multi-code MC-CDMA using FDAIC, and discussed the impact of spreading factor *SF*. It was shown that, using FDAIC, more accurate residual ICI replica can be generated for ICI cancellation as the code-multiplexing order increases. When the low coding rate and high level modulation are used, OFDM (SF=C=1) provides slightly better BER performance than MC-CDMA with FDAIC. However, in the uncoded case, the full code-multiplexed MC-CDMA with FDAIC using the full spreading factor (SF=C=N_c) can provide better BER performances than OFDM. It was also shown that the throughput performance of full code multiplexed MC-CDMA with FDAIC is almost the same or better than OFDM over entire range of E_s/N_0.

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