

RCPT 符号化ハイブリッド ARQ を用いた MC-CDMA の最適拡散率 に関する考察

ガーグ・ディープシカ[†] 安達 文幸[‡]

† ‡ 東北大学大学院工学研究科電気通信工学専攻
〒980 - 8579 宮城県仙台市青葉区荒巻字青葉 05

E-mail: † deep@mobile.ecei.tohoku.ac.jp, ‡ adachi@ecei.tohoku.ac.jp

あらまし MC-CDMA では、周波数領域で定義された直交拡散符号を用いて、データシンボルを多数のサブキャリアに拡散する。拡散率 SF が大きくなるにつれ大きな周波数ダイバーシチ効果が得られるため伝送特性が改善するものの、1 ユーザ当たりの伝送レートが低下してしまう。 $SF=1$ を用いる MC-CDMA は OFDM である。MC-CDMA では拡散率と同数のユーザを多重させると OFDM と同等の総合スループットを達成できる。本論文では、RCPT 符号化ハイブリッド ARQ を用いた MC-CDMA について、総合スループットを最大とする意味での最適な拡散率を明らかにしている。

キーワード hybrid ARQ, rate compatible punctured turbo codes, frequency selective channel, MC-CDMA, mobile communications

Analysis of the optimum spreading factor for MC-CDMA with RCPT-coded HARQ

Deepshikha GARG[†] and Fumiyuki ADACHI[‡]

† ‡ Department of Electrical and Communication Engineering, School of Engineering, Tohoku University
Aza-Aoba 05, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

E-mail: † deep@mobile.ecei.tohoku.ac.jp, ‡ adachi@ecei.tohoku.ac.jp

Abstract In MC-CDMA, each user's data-modulated symbol to be transmitted is spread over a number of subcarriers using an orthogonal spreading sequence defined in the frequency-domain. As the spreading factor SF becomes larger, the transmission performance improves due to increasing frequency diversity effect; however, the data rate per user decreases. The $SF=1$ system corresponds to an OFDM system. In an MC-CDMA system the same total throughput as in the OFDM system can be achieved if the number of users allowed to transmit simultaneously is the same as SF . In this paper, we investigate the optimum spreading factor for MC-CDMA when rate compatible punctured turbo coded hybrid ARQ (RCPT HARQ) is used for error control. It was found that when many strong paths exist, the total downlink throughput is highest when the data is spread over all the subcarriers available; however the highest total uplink throughput is attained with an OFDM system ($SF=1$).

Keyword hybrid ARQ, rate compatible punctured turbo codes, frequency selective channel, MC-CDMA, mobile communications

1. Introduction

In mobile radio communications, the transmitted signal is scattered by many obstacles located between a transmitter and a receiver, thereby creating a propagation channel with numerous paths having different time delays. The transfer function of such a channel is no more constant over the signal bandwidth and is referred to as the frequency-selective channel [1].

Direct sequence code division multiple access (DS-CDMA) spreads the data modulated symbol to be transmitted over a wide bandwidth to take advantage of the multipath channel by employing rake receivers; however it suffers from inherent inter-symbol-interference when high speed data applications are considered. Recently, a new CDMA system based on the combination of CDMA and multicarrier (MC) modulation based on orthogonal frequency division multiplexing, called MC-CDMA, has been attracting much attention and is under extensive study [2, 3].

In MC-CDMA, each user's data-modulated symbol to be transmitted is spread over a number of subcarriers using an orthogonal spreading sequence defined in the frequency-domain. Since the received signal suffers from frequency selective fading, the orthogonality among different users' signals is partially lost, resulting in a large multi-user interference (MUI). However, the orthogonality property can be partially restored while achieving the frequency diversity effect by using a simple one-tap equalization per subcarrier [2, 3] and hence, a better bit error rate (BER) performance can be achieved.

In all types of data transmission systems, some form of error control is needed to mitigate the adverse effects of fading. In [4] RCPT HARQ is applied to a DS-CDMA system and it is shown that the throughput is almost same with and without spreading in a frequency selective channel. In MC-CDMA, larger spreading factor SF achieves larger frequency diversity effect in a frequency selective channel. A total of SF users can communicate simultaneously; higher SF allows more simultaneously communicating users. However, the data rate per user decreases with increasing spreading factor for a fixed transmission bandwidth. In this paper, we investigate the optimum spreading factor, from the point of view of maximizing the total throughput, for MC-CDMA when RCPT HARQ is used for error control. The evaluation is done by computer simulation for a frequency selective channel.

The remainder of this paper is organized as follows. Section II describes the RCPT HARQ scheme considered in this paper. The transmission system model using MC-CDMA is presented in section III. In section IV, the performance evaluation is done via computer simulations for a single user and multi-user case. Section V offers some conclusions and future work.

2. RCPT HARQ

The RCPT encoder and decoder are shown in Fig. 1. The RCPT encoder consists of a turbo encoder, a puncturer, and a

buffer. Likewise an RCPT decoder consists of a buffer, de-puncturer, and a turbo decoder.

The turbo encoder considered in this paper is a rate 1/3 encoder. The turbo encoder/decoder parameters are shown in Table 1. Type II HARQ is considered in this paper that is obtained by puncturing the parity sequences got after turbo coding with a puncturing period of $P=8$ as it was found that transmitting minimum amount of redundancy bits with each retransmission gives the highest throughput [4]. The first transmission consists of transmitting the sequence corresponding to the systematic bits. Since the systematic bits are the information bits themselves, no decoder is needed. Error detection is performed on the received signal sample sequence and if error is detected, a retransmission request or a negative acknowledgement (NAK) is sent; the punctured parity bit sequence is transmitted. Upon reception of a part of the punctured sequence, the de-puncturer inputs the received signal sample sequences corresponding to the systematic bits and the punctured parity bits to the decoder. A channel value of zero is inserted for those parity bits that are not yet transmitted and hence not received. The decoding algorithm remains the same irrespective of the puncturing pattern and decoding with 8 iterations is performed as if three sequences were received.

After iterative decoding, error detection is performed and detection of error causes another retransmission request; the second punctured parity bit sequence is transmitted. Previously received sequences are used together with the newly received sequence for turbo decoding. The retransmission continues until an error-free detection is performed. The puncturing matrixes used to obtain the sequences transmitted in subsequent transmissions are as follows (in octal notation):

$$\begin{bmatrix} 3 & 7 & 7 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 2 \\ 0 & 4 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 4 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 2 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 4 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 2 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

The first transmission consists of K bits (K is the length of information bits with error detection parity bits) whereas successive transmissions consist of $K/4$ bits each. After the 9th transmission, all the sample sequences, corresponding to the systematic bits, parity1 bits and parity 2 bits, are received. Presence of errors even after the 9th transmission causes the sequences of systematic bits, parity1 bits and parity 2 bits to be transmitted again in the 10th ~ 18th transmissions and the time diversity combining [5] or Chase combining [6] is employed in addition to incremental redundancy [7].

Table 1: Turbo encoder/decoder parameters

Encoder	Rate	1/3
	Component encoder	(13, 15) RSC
	Interleaver	S-random ($S=K^{1/2}$)
Decoder	Component decoder	Log-MAP
	Number of iterations	8

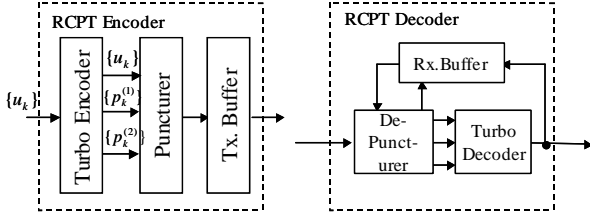


Fig. 1 RCPT Encoder/Decoder

3. Transmission System Using RCPT HARQ

An equivalent low-pass transmission system model is illustrated in Fig. 2.

3.1 Transmitter

The transmitter is composed of a CRC encoder, an RCPT encoder, a channel bit-interleaver, a binary phase shift keying (BPSK) data modulator, a serial-to-parallel (S/P) converter, and an inverse fast Fourier transformer. The CRC encoder adds the error detection parity check sequence to a binary data sequence $\{d_k\}$ of length K to form a CRC encoded sequence $\{u_k\}$ of length K which is input to the RCPT encoder. The turbo encoder output sequences $\{u_k\}$, $\{p_k^{(1)}\}$, $\{p_k^{(2)}\}$ are punctured by puncturing matrices described in the previous section and the resulting sequences are buffered for possible retransmissions. The punctured sequence that is to be transmitted is block-interleaved by the channel interleaver and transformed into BPSK symbol

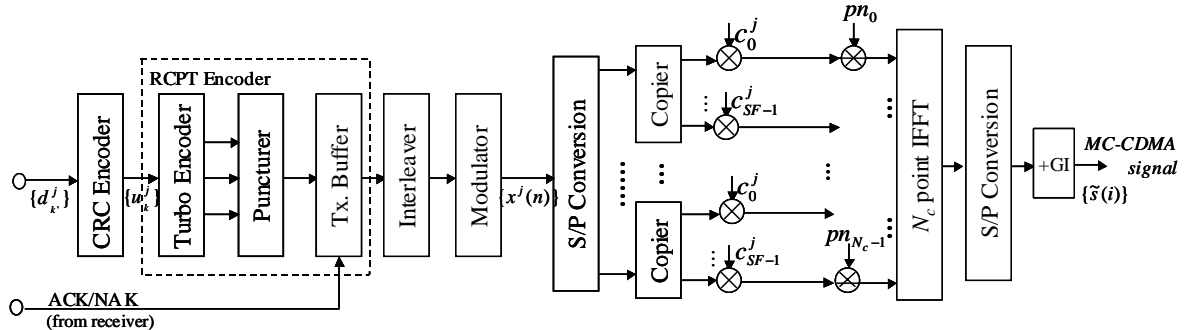
sequence. The modulated signal is spread over multiple subcarriers and transmitted.

Throughout the paper, discrete-time representation of the MC-CDMA signal has been adopted. We consider MC-CDMA having N_c subcarriers with a carrier spacing of $1/T_s$. Each user's data is spread using the frequency domain orthogonal (Walsh-Hadamard) spreading code with a spreading factor SF . Let $x^j(n)$ be the j th user's n th data-modulated symbol with $|x^j(n)| = 1$. During $0 \leq t < T$,

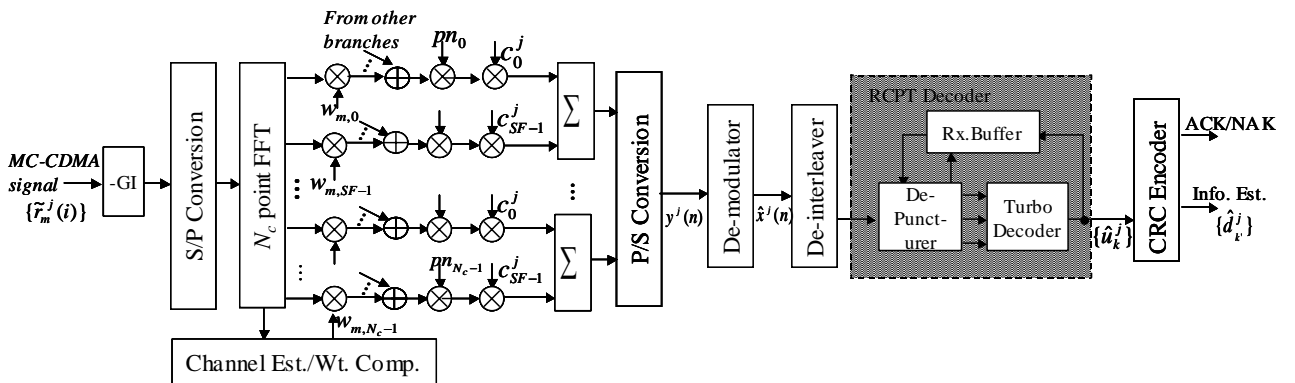
$\{x^j(n); n = 0 \sim \lfloor N_c / SF \rfloor - 1\}$ is transmitted, where $\lfloor a \rfloor$ denotes the largest integer smaller than or equal to a . The S/P converter converts the serial data into N_c/SF parallel data streams, each of which is copied SF times and multiplied by $c_j(t) = [c_0^j c_1^j c_2^j \dots c_{SF-1}^j]$, the spreading code for user j , and further multiplied by $\{pn_k; k = \dots, 0, 1, \dots\}$, the long scramble sequence. The k th subcarrier component s_k may be expressed using the equivalent baseband representation as

$$s_k = \sqrt{\frac{2A}{SF}} c_{k \bmod SF}^j pn_k x^j \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) \quad (1a)$$

for $k = 0 \sim N_c - 1$, where A represents the transmit power of each user. Eq. (1a) represents the uplink. In the downlink case, N users' symbols are multiplexed after spreading with different orthogonal spreading codes and then further



(a) Transmitter



(b) Receiver

Fig. 2 Transmission system model

multiplied by a common long scramble sequence $\{pn_k; k = \dots, 0, 1, \dots\}$. Hence s_k is given by

$$s_k = \sum_{j=0}^{N-1} \sqrt{\frac{2A}{SF}} c_{k \bmod SF}^j pn_k x^j \left(\left\lfloor \frac{k}{SF} \right\rfloor \right). \quad (1b)$$

N_c -point inverse fast Fourier transform (IFFT) is applied to the sequence $\{s_k; k = 0 \sim N_c - 1\}$ to generate the MC-CDMA signal $\{s(i); i = 0 \sim N_c - 1\}$:

$$s(i) = \frac{1}{N_c} \sum_{k=0}^{N_c-1} s_k \exp\left(j2\pi k \frac{i}{N_c}\right). \quad (2)$$

After insertion of the N_g -sample guard interval (GI), the resultant MC-CDMA signal $\{\tilde{s}(i); i = -N_g \sim N_c - 1\}$ is transmitted over a propagation channel, where

$$\tilde{s}(i) = s(i \bmod N_c). \quad (3)$$

Without loss of generality, we consider the time interval of one MC-CDMA symbol length, i.e., $0 \leq t < T$ with $T = T_s + T_g$, where T_s and T_g are respectively the effective symbol length and the GI. Since the IFFT sampling period is $\Delta T = T_s / N_c$, we have $T_g = N_g \Delta T$ and $T = T_s + T_g = T_s(1 + N_g / N_c)$.

3.2 Propagation Channel Model

A ΔT -spaced delay-time model for the propagation channel is assumed. M -branch antenna diversity reception is used at a receiver. Assuming L independent propagation paths with distinct time delays $\{\tau_l^j\}$, the impulse response $\xi_{m,l}^j(\tau)$ of the multipath channel experienced by the m th antenna, $m=0 \sim M-1$, may be expressed as

$$\xi_{m,l}^j(\tau) = \sum_{l=0}^{L-1} \xi_{m,l}^j \delta(\tau - \tau_l) \quad (4)$$

with $\sum_{l=0}^{L-1} E[|\xi_{m,l}^j|^2] = 1$, where superscript j denotes the user index, $\delta(t)$ is the delta function and $E[\cdot]$ denotes ensemble average. The time delays $\{\tau_l^j\}$ are assumed to be multiples of the FFT sampling period. Time dependency of the channel has been dropped for simplicity. The power delay profile is shown in Fig. 3. $E[|\xi_{m,l}^j|^2]$, $l = 0 \sim L-1$, are assumed to be exponentially decreasing with coefficient β and decay factor α , where β is given by $\beta = [1 - \exp(-\alpha)] / [1 - \exp(-L\alpha)]$. When $\alpha \rightarrow 0$, we get a uniform power delay profile with the average power per path equal to $1/L$. The channel is characterized by the delay spread τ_{rms} defined as

$$\tau_{rms} = \sqrt{\overline{\tau^2} - \bar{\tau}^2} \quad (5)$$

where, $\overline{\tau^2} = \sum_{l=0}^{L-1} E[|\xi_{m,l}^j|^2] (\tau_l^j)^2$ and $\bar{\tau} = \sum_{l=0}^{L-1} E[|\xi_{m,l}^j|^2] \tau_l^j$.

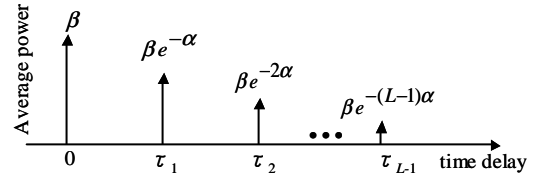


Fig. 3 Power delay profile model.

3.3 Receiver

As shown in Fig. 2, the MC-CDMA receiver consists of a fast Fourier transformer, a coherent demodulator, a bit de-interleaver, an RCPT decoder and a CRC decoder.

The MC-CDMA signal received on the m th antenna is sampled at the rate of $\Delta T^{-1} = N_c / T_s$ to obtain $\{\tilde{r}_m(i); i = -N_g \sim N_c - 1\}$, which is expressed as

$$\tilde{r}_m(i) = \sum_{l=0}^{L-1} \xi_{m,l}^j \tilde{s}(i - \tau_l / \Delta T) + \eta_m(i), \quad (6)$$

where $\eta_m(i)$ represents the additive white Gaussian noise (AWGN) process. The N_g -sample GI is removed and the N_c -point fast Fourier transform (FFT) is applied to decompose the received MC-CDMA signal into the N_c -subcarrier components $\{r_{m,k}; k = 0 \sim N_c - 1\}$:

$$r_{m,k} = \sum_{i=0}^{N_c-1} \tilde{r}_m(i) \exp\left(-j2\pi k \frac{i}{N_c}\right) \quad (7)$$

for $m=0 \sim M-1$. Denoting the channel gain at the k th subcarrier on the m th antenna by $H_{m,k}$, the k th subcarrier component $r_{m,k}$ received on the m th antenna may be represented as

$$r_{m,k} = \begin{cases} H_{m,k} \sum_{j=0}^{N-1} \sqrt{\frac{2A}{SF}} c_{k \bmod SF}^j pn_k x^j \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) + \eta_{m,k} \\ \text{for downlink} \\ \sum_{j=0}^{N-1} H_{m,k}^j \sqrt{\frac{2A}{SF}} c_{k \bmod SF}^j pn_k x^j \left(\left\lfloor \frac{k}{SF} \right\rfloor \right) + \eta_{m,k} \\ \text{for uplink} \end{cases}, \quad (8)$$

where $\{H_{m,k}^j; k = 0 \sim N_c - 1\}$ and $\{\eta_{m,k}; k = 0 \sim N_c - 1\}$ are respectively the Fourier transforms of the channel impulse response $\xi_{m,l}^j(\tau)$ and the AWGN process $\eta_m(i)$. They are given by

$$\begin{cases} H_{m,k}^j = \sum_{l=0}^{L-1} \xi_{m,l}^j \exp\left(-j2\pi k \frac{\tau_l / \Delta T}{N_c}\right) \\ \eta_{m,k} = \sum_{i=0}^{N_c-1} \eta_m(i) \exp\left(-j2\pi k \frac{i}{N_c}\right) \end{cases}, \quad (9)$$

where $\{H_{m,k}^j\}$ are the independent and identically distributed (iid) complex random variables with zero mean and unit variance and $\{\eta_{m,k}\}$ are the iid complex Gaussian variables with zero mean and variance $2N_0/T_s$, with N_0 representing the single sided AWGN power spectrum density.

For the frequency-domain despreading, minimum mean square combining (MMSEC) [2, 3] is considered. On each subcarrier, the M received signal samples are weighted by $\{w_{m,k}; m=0 \sim M-1\}$ and combined to obtain

$$y_k = \sum_{m=0}^{M-1} w_{m,k} r_{m,k}, \quad (10)$$

where $\{w_{m,k}; m=0 \sim M-1\}$ are the MMSEC weights given by [2, 3, 8]

$$w_{m,k} = \begin{cases} \frac{H_{m,k}^*}{\sum_{m=0}^{M-1} |H_{m,k}|^2 + \left(\frac{N}{SF} \frac{AT_s}{N_0}\right)^{-1}} & \text{for downlink} \\ \frac{H_{m,k}^{j*}}{\sum_{j=0}^{N-1} \sum_{m=0}^{M-1} |H_{m,k}^j|^2 + \left(\frac{1}{SF} \frac{AT_s}{N_0}\right)^{-1}} & \text{for uplink} \end{cases}. \quad (11)$$

The weighted samples are first multiplied by the complex conjugate of the scrambling sequence $\{pn_k^*\}$. To obtain the decision variable $y^j(n)$ for the n th data-modulated symbol of the j th user, despreading is performed by multiplying SF soft samples $\{y_k; k=nSF \sim (n+1)SF-1\}$ by the orthogonal spreading code $\{c_{k \bmod SF}^j; k=nSF \sim (n+1)SF-1\}$ and the scramble code $\{pn_k\}$, and summing them up:

$$y^j(n) = \sum_{k=nSF}^{(n+1)SF-1} y_k c_{k \bmod SF}^{j*} pn_k^*, \quad (12)$$

where $*$ denotes the complex conjugate operation. $\{y^j(n); n=0 \sim \lfloor N_c / SF \rfloor - 1\}$ is the coherently detected soft decision sample sequence that is de-interleaved and input to the RCPT decoder, where error correction is performed and the CRC coded sequence estimate $\{\hat{u}_k^j\}$ is obtained. If no error is detected, the CRC decoder outputs the sequence $\{\hat{d}_k^j\}$ as the received information bit sequence. In the case of errors being detected by the CRC decoder, a retransmission is requested.

4. Performance Evaluation

The throughput performance of RCPT HARQ in a frequency selective Rayleigh fading channel with antenna diversity reception is evaluated by computer simulations. The computer simulation conditions are summarized in Table 2. The turbo encoder/decoder parameters are as shown in Table 1. The channel interleaver used in the simulation is a size $2^a \times 2^b$ block interleaver, where a and b are the maximum allowable integers for a given sequence size and are determined so that an interleaver as close as possible to a square interleaver can be obtained. We assume MC-CDMA using $N_c = 256$ subcarriers with a carrier spacing of $1/T_s$, a guard interval of $T_g = T_s/8$ (i.e., $N_g = 32$) and ideal coherent BPSK data modulation/ demodulation. IFFT and FFT sampling period ΔT is $\Delta T = T_s/256$.

Uncorrelated, time-varying Rayleigh faded paths are generated using Dent's model [9]. An exponential power delay profile is considered. The number of propagation paths $L=16$, the propagation time delay difference between the nearest two paths $\tau_l = 2\Delta T$, and the maximum normalized Doppler frequency $f_d T = 0.01$. $\alpha=0$ is assumed unless otherwise stated.

In the following simulations the frame length $K = 1024$ bits (frame length represents the CRC encoded sequence length). Throughput efficiency η is defined as in [7]

$$\eta = \frac{\text{Bits transmitted successfully}}{\text{Total number of bits transmitted}}. \quad (13)$$

An error-free reverse channel and ideal error detection are assumed. The number of retransmissions is taken to be infinite.

Table 2 Simulation condition

Frame length	1024	
Channel coding	Turbo coding	
Interleaver	Block interleaver	
Data Modulation	BPSK	
MC-CDMA	No. of subcarriers	$N_c=256$
	Effective symbol length	$T_s=256\Delta T$
	Guard interval	$T_g=32\Delta T$ ($T_g/T_s=1/8$)
	Spreading factor	$SF=1 \sim 256$
Channel model	Data channel	Rayleigh fading ($L=16$)
		$\tau_l = 2\Delta T$
	ARQ channel	Ideal

4.1 Single User Case

4.1.1 BER Performance

Figure 4 plots the simulated average bit error rate (BER) performances of turbo-coded MC-CDMA as a function of the average received signal energy per information bit to the noise power spectrum density ratio (E_b/N_0) with the spreading factor (SF) as a parameter where

$E_b/N_0=9/8(AT_s/N_0)$. It is seen that the average BER performance continuously improves as the spreading factor increases; the use of $SF=256$ reduces the required average received E_b/N_0 for $BER=10^{-4}$ by as much as about 7dB compared to OFDM ($SF=1$). This is because each modulated symbol is spread over multiple subcarriers and the frequency diversity effect is achieved. Hence spreading the data symbols over multiple subcarriers gives better BER due to increased frequency diversity effect.

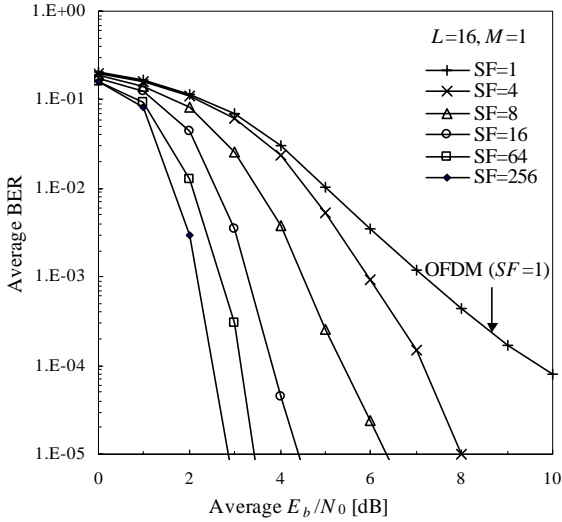
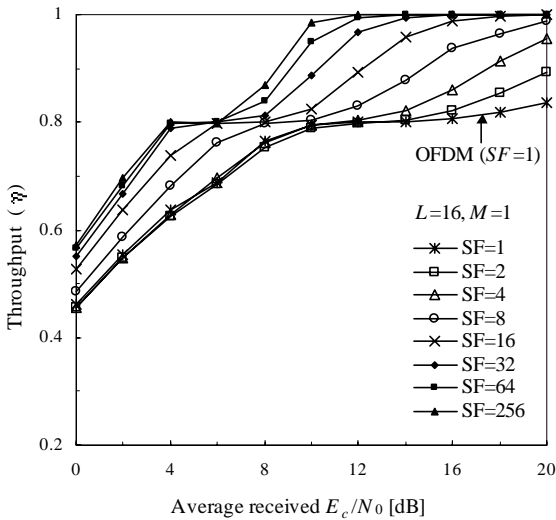


Fig. 4 BER performance ($N=1$). $L=16$ and $M=1$.

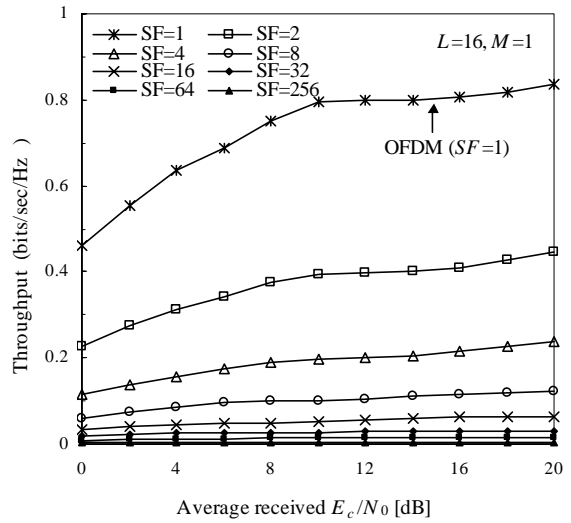
4.1.2 Throughput Performance



(a) Throughput η .

The throughput of the RCPT coded type II HARQ is plotted in Fig. 5(a) as a function of the average received signal energy per coded bit to the noise power spectrum density ratio (average received E_c/N_0) with SF as a parameter for the normalized rms delay spread $\tau_{rms}/T_s = 0.036$ ($\alpha=0$ dB). It is seen that the throughput increases as the spreading factor increases. This is due to the same reason as to why the BER improves. However as the SF increases, the data rate decreases and hence the throughput in bits/sec/Hz (bps/Hz) is seen to decrease drastically with the increase in

SF as shown in Fig. 5(b). OFDM ($SF=1$) is found to provide the largest throughput in bps/Hz.



(b) Throughput $\eta_{bits/sec/Hz}$.
Fig. 5 Throughput performance. $L=16$ and $M=1$.

4.2 Multiple Users case

4.2.1 BER Performance

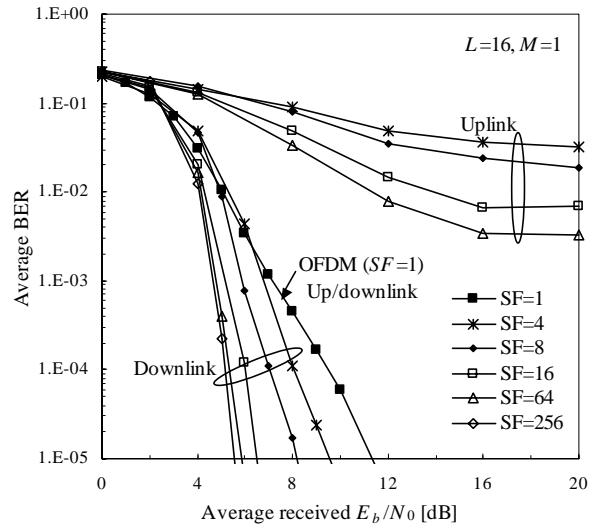


Fig. 6 BER performance ($N=SF$). $L=1$ and $M=1$.

When there are multiple users communicating simultaneously, the uplink and downlink performances are different. In the uplink case, the data is transmitted by users distributed at geographically different locations whereas in the downlink case, the data is transmitted from the base station. The BER performance of turbo coded MC-CDMA in the multiuser case is plotted in Fig. 6 with SF (= the number of users N) as a parameter. Note that, in the uplink, slow transmit power control is assumed so that the signals of all users are received with the same average power. However the users' transmitting timings are asynchronous and uniformly distributed over $0 \sim T$. It is seen that in the downlink case, the BER improves with the increase in SF due to increased frequency diversity effect. Due to the

existence of multiple users, the improvement is less than that for the single user case; a 5dB gain in the average received E_b/N_0 is attained for a BER= 10^{-4} when SF changes from 1 to 256. In the uplink case, error floor occurs in the BER performance because of the asynchronism among the users. However, as the SF increases the turbo coded BER improves slightly.

4.2.2 Throughput Performance

A. Downlink

Figure 7 plots the total downlink throughput with SF as a parameter when the total number of users (N) = SF . (The total bit rate is kept the same as in OFDM.) It is seen that the total throughput is almost independent of SF for lower average E_c/N_0 however, for higher average E_c/N_0 , the throughput increases with increasing SF . The $SF=1$ system corresponds to an OFDM system. It suggests that using an OFDM system with some form of time scheduling is as good as using an MC-CDMA system with multiple simultaneously communicating users when the average received E_c/N_0 is less than 8dB. However, when the channel condition is good, it may be better to spread the data over multiple carriers. Using $SF=N_c$ gives the highest total throughput. When $N < N_c$, multiple codes can be assigned to each of these users in communication to improve the throughput of the communicating users.

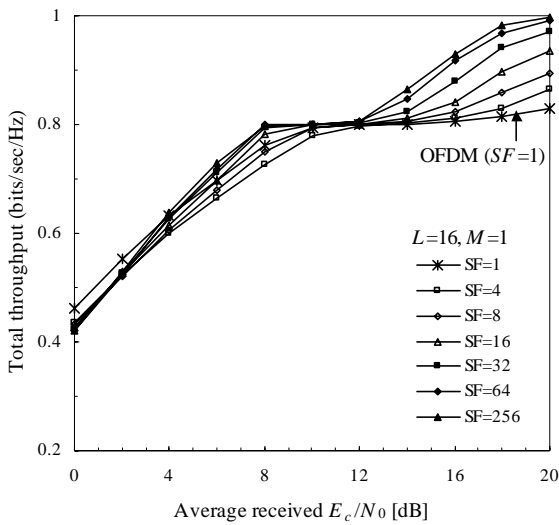


Fig. 7 Total downlink throughput ($N=SF$). $L=16$ and $M=1$.

B. Uplink

As seen from Figure 6, the BER performance degrades due to the asynchronism among the users. However, when RCPT code is used for error correction together with ARQ, the throughput is not zero in spite of a very bad BER performance due to incremental redundancy and time diversity or Chase combining. It can be seen in Fig. 8 that the throughput increases slightly with the increase in the spreading factor. It should be noted that in this paper, we assume that the total number of communicating users is the same as the spreading factor. Hence for the uplink case, it is the best to use an OFDM system with some form of time scheduling to allow only one user to communicate at a time.

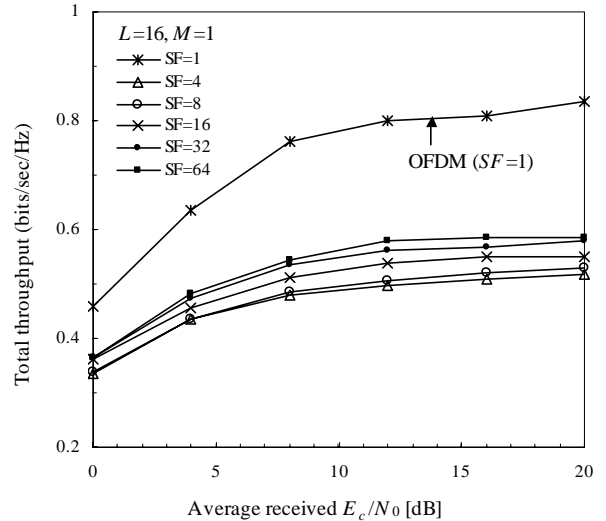


Fig. 8 Total uplink throughput ($N=SF$). $L=16$ and $M=1$.

4.3 Diversity Reception

The effect of antenna diversity is analyzed in this section. For both the uplink and downlink cases, 2-antenna maximum ratio combining (MRC) receive diversity is assumed. The results of computer simulations are plotted in Fig. 9. It is seen that with diversity reception, the throughput improves for both downlink and uplink compared to the no diversity case. However the dependence of throughput on SF is identical to that of no diversity.

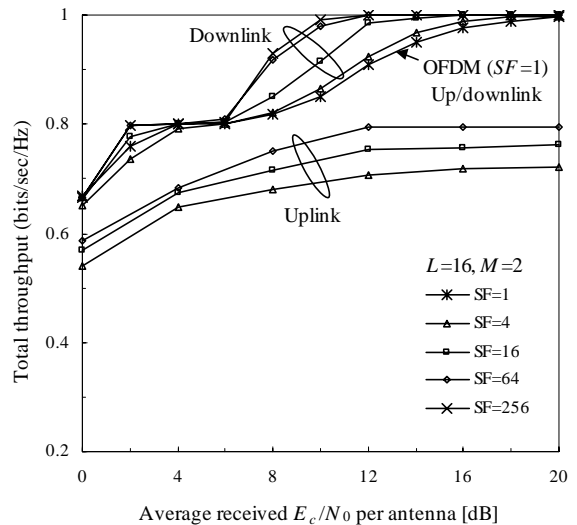


Fig. 9 Total throughput ($N=SF$). $L=16$ and $M=2$.

4.4 Power Delay Profile of the Channel

The evaluations done until now were for a channel with $L=16$ and a uniform power delay profile ($\alpha=0$). In this section we analyze how the delay spread of the channel changes the optimum spreading factor. Figure 10 plots the throughput as a function of average received E_c/N_0 with τ_{rms}/T_s as a parameter for $M=2$. We saw in Fig. 7 that for $\tau_{rms}/T_s = 0.036$ ($\alpha=0$), the use of $SF=256$ ($SF=1$) gives the highest (lowest) throughput. However when $\tau_{rms}/T_s=0.0036$ ($\alpha = 8$ dB) the throughput for $SF=1$ is higher than that for $SF=256$. $\tau_{rms}/T_s=0.0036$ corresponds to a channel with one

strong path. Hence when multiple strong paths exist it is better to spread the data over multiple subcarriers but in a single path channel it is best to use an OFDM system ($SF=1$) with one user at a time. In the uplink case as well the throughput decreases with decreasing delay spread for larger SF due to decreased diversity effect. Figure 10 shows that the throughput for $SF=64$ decreases by about 10% when $\tau_{rms}/T_s = 0.0036$ compared to when $\tau_{rms}/T_s = 0.036$. The throughput for OFDM ($SF=1$) increases with the decrease in delay spread. Hence for uplink, the OFDM system gives the highest throughput irrespective of the channel delay spread.

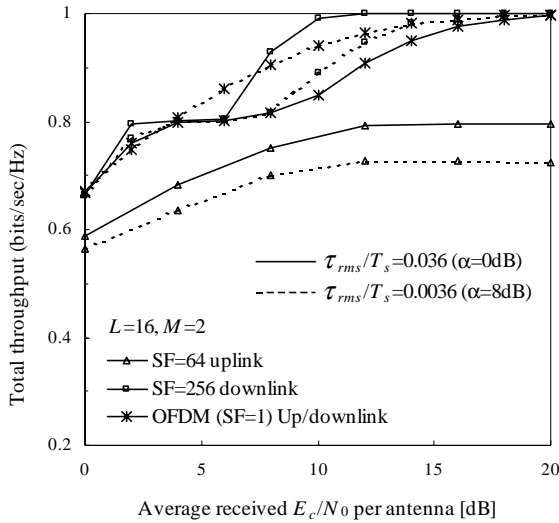


Fig. 9 Total throughput ($N=SF$). $L=16$ and $M=2$.

5. Conclusion

The optimum spreading factor of the MC-CDMA when RCPT HARQ is used for error correction is evaluated. It was found that different accessing techniques will be required for uplink and downlink to maximize the throughput for each link. For downlink, MC-CDMA gives the highest total throughput when the data is spread over all the subcarriers available, i.e., $SF=N_c$. SF users can communicate simultaneously but the data rate per user decreases. When the number of users who want to communicate is less than the number of subcarriers, multiple codes can be assigned to each of these users to improve their throughput. On the other hand, in the uplink case, asynchronism among the users results in decreased throughput when $SF>1$; the highest total

uplink throughput is attained with an OFDM system ($SF=1$), i.e., only one user communicates at a time. However some form of time scheduling to allow only one user to communicate at a time will be necessary. Multicode MC-CDMA is an alternative to the OFDM system wherein the frequency diversity effect can be availed [10].

For bridging MC-CDMA and OFDM, multirate MC-CDMA systems employing variable OVSF [11] may be a good solution. Further study in this direction is needed.

References

- [1] W. C., Jakes Jr., Ed., *Microwave mobile communications*, Wiley, New York, 1974.
- [2] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels," *IEEE Trans. Veh. Tech.*, Vol. 48, pp. 1584-1595, Sept. 1999.
- [3] S. Hara and R. Prasad, "Overview of multicarrier CDMA", *IEEE Commun. Mag.*, pp.126-144, Dec. 1997.
- [4] D. Garg, R. Kimura and F. Adachi, "A Comprehensive Performance Evaluation of Turbo-coded Hybrid ARQ for DS-SS-CDMA in a Frequency Selective Rayleigh Fading Channel", Technical Report of IEICE RCS2001-280, p.p. 241-248, March. 2002.
- [5] F. Adachi, S. Ito, and K. Ohno, "Performance analysis of a time diversity ARQ in land Mobile radio", *IEEE Trans. Communications*, Vol. 37, pp.177-183, Feb. 1989.
- [6] D. Chase, "Code combining- A maximum likelihood decoding approach for combining an arbitrary number of noisy packets", *IEEE Trans. Communications*, Vol. COM-33, pp. 385-393, May 1985.
- [7] J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their application", *IEEE Trans. Communications*, Vol. 36, pp.389-400, April. 1988.
- [8] T. Sao, F. Adachi, "マルチレート MC-CDMA 信号のダイバシチ受信についての考察", Technical Report of IEICE RCS2002-204, Nov. 2002.
- [9] P. Dent, G. E. Bottomley, and T. Croft, "Jakes fading model revisited", *Electronics Letters*, Vol. 29, No. 13, June 1993.
- [10] D. Garg and F. Adachi, "On the Spreading Factor of Multicode MC-CDMA with RCPT Hybrid ARQ", 信学会総合大会, 東北大学, March 2003.
- [11] F. Adachi, M. Sawahashi, and K. Okawa, "Tree-structured generation of orthogonal spreading codes with different lengths for forward link of DS-SS-CDMA mobile radio," *IEE Electron. Lett.*, vol. 33, pp. 27-28, Jan. 1997.