社団法人 電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE

RCPT ハイブリッド ARQ の OFDM，マルチコード DS-CDMA とマルチコード MC-CDMA への応用と特性比較

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 OFDM，MC-CDMA および DS-CDMA は，次世代のブロードバンド移動体通信システムにおける無線伝送技術として期待されており，最近活発に研究されている．高速高品質データ通信における重要な誤り制御技術として知られているのがハイブリッド ARQ(HARQ)である．符号化率可変ターボ符号化(RCPT)HARQ は有望な技術の１つである．マルチコード MC-CDMA およびマルチコード DS-CDMA では一人のユーザに利用可能なコードをすべて割り当てることにより，OFDM と等しいデータレートを実現できる．本論文では，OFDM と同じ伝送レートのもとで RCPT HARQ を用いる OFDM，マルチコード MC-CDMA およびマルチコード DS-CDMA のスループット特性を比較している．

キーワード OFDM, multicode MC-CDMA, multicode DS-CDMA, MMSE equalization, RCPT HARQ

Application of Turbo-coded Hybrid ARQ to OFDM, Multicode DS-CDMA and Multicode MC-CDMA and their Performance Comparison

Deepshikha GARG† and Fumiyuki ADACHI‡

†‡Department of Electrical and Communication 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 OFDM, MC-CDMA and DS-CDMA are being researched vigorously as the prospective signaling technique for the next generation of mobile communications systems, which will be characterized by the broadband packet technology. With packet transmission, hybrid ARQ (HARQ) will be inevitable for error control. HARQ with rate compatible punctured turbo (RCPT) codes is one of the promising techniques. Data rate equivalent to the OFDM system can be attained with MC-CDMA and DS-CDMA by assigning all the available codes to the same user resulting in what is commonly referred to as multicode MC-CDMA and multicode DS-CDMA. In this paper we compare the throughput performance of OFDM, multicode MC-CDMA and multicode DS-CDMA when RCPT HARQ is used for error control.

Keyword OFDM, multicode MC-CDMA, multicode DS-CDMA, MMSE equalization, RCPT HARQ

1. Introduction

Broadband wireless packet technology is one of the core technologies for the next generation of mobile communications systems. Direct sequence code division multiple access (DS-CDMA) [1], orthogonal frequency division multiplexing (OFDM) [2] and multi-carrier code division multiple access (MC-CDMA) [3], [4] are the major contenders for wireless signaling technique. The bit error rate (BER) performances of these schemes have been compared in some recent publications [2], [3], [4]. However, for packet transmission some form of error control technique is necessary. Hybrid ARQ (HARQ) with rate compatible punctured turbo (RCPT) codes is one promising technique [5], [6]. In this paper we compare the throughput performance of OFDM, MC-CDMA and DS-CDMA when RCPT HARQ is used for error control. For a fair comparison we keep the transmission rate fixed as that attainable with an OFDM system.

The data rate equivalent to the OFDM system can be realized with DS-CDMA by assigning all the available codes, equal to the spreading factor SF_{DS}, to the same user resulting in what is commonly referred to as multicode DS-CDMA [7]. In MC-CDMA with the same number of subcarriers as in OFDM, when the number of multiplexed codes is the same as the spreading factor SF_{MC}, the transmission rate is the same as in OFDM. MC-CDMA with $SF_{MC}=1$ is in fact the OFDM system. It is shown that larger SF_{MC} provides a better bit error rate (BER) performance [8]. It is concluded in [9] that having SF_{MC} equal to the number N_c of subcarriers available gives the highest throughput performance at all times, so in the this paper we take $SF_{MC}=N_c$ for MC-CDMA.

The rest of the paper is organized as follows. The overall transmission system model is presented in Section 2. Section 3 reviews the basics of the 3 signaling techniques. RCPT HARQ schemes considered in this paper are presented in Section 4. The simulation results are presented and discussed in Section 5. Section 6 concludes the paper.

2. Transmission System Model

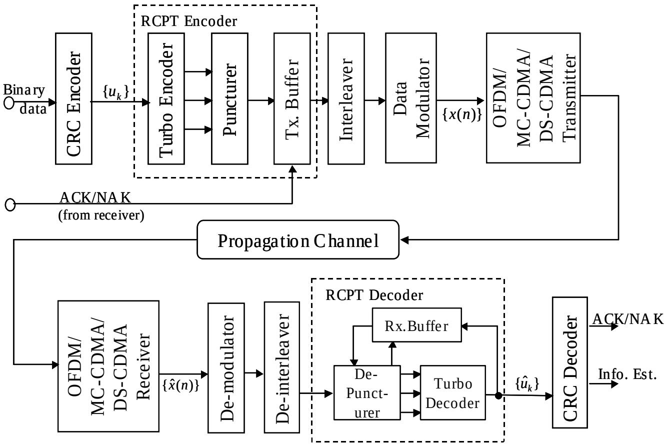


Figure 1. Transmission system model.

The transmission system model is shown in Fig. 1. The transmitter consists of a CRC encoder, an RCPT encoder, a bit interleaver, and a data modulator followed by an OFDM, MC-CDMA or DS-CDMA transmitter. The CRC encoder adds the error detection parity check sequence to a binary data sequence to form a CRC encoded sequence $\{u_k\}$ of length K which is input to the RCPT encoder. The rate 1/3 turbo encoder output sequences, the systematic bit sequence $\{u_k\}$ and the two parity bit sequences $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$, are punctured according to the puncturing patterns of different RCPT HARQ schemes as described in Section 3 and the resulting sequences are buffered for possible retransmissions. The punctured sequence that is to be transmitted is bit interleaved and data-modulated. Let the data-modulated symbol sequence be $\{x(n)\}$ with $|x(n)|=1$ and symbol length T. It is then transmitted as OFDM, MC-CDMA or DS-CDMA signal as described in the next section.

It is assumed that the propagation channel has L discrete paths having different time delays and experiencing independent Rayleigh fading. The channel impulse response $\xi(t,\tau)$ at time t can be expressed as [10], [11]

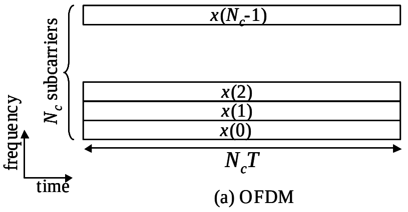
$$\xi(t,\tau)=\sum_{l=0}^{L-1}\xi_l(t)\delta(\tau-\tau_l)\quad,\quad(1)$$

where $\xi_l(t)$ and τ_l denote the complex path gain at time t and the time delay of the lth path, respectively, with $E[\sum_{l=0}^{L-1}|\xi_l(t)|^2]=1$, here E[.] denotes the ensemble average operation and $\delta(.)$ denotes the delta function. It is assumed that $\{\xi_l(t);\ l=0\sim L\text{-}1\}$ are independent zero-mean complex Gaussian processes. $E[|\xi_l(t)|^2]$, $l=0\sim L-1$, are assumed to be exponentially decreasing with coefficient β and exponent α, where β is given by $\beta=[1-\exp(-\alpha)]/[1-\exp(-L\alpha)]$. When $\alpha\to 0$, we get a uniform power delay profile with the average power per path equal to $1/L$.

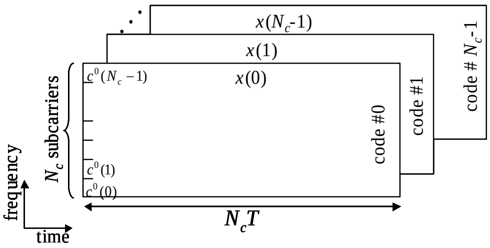
The receiver consists of a data-demodulator, a bit deinterleaver, an RCPT decoder and a CRC decoder in addition to an OFDM, MC-CDMA or DS-CDMA specific receiver. The recovered symbol sequence $\{\hat{x}(n)\}$ is demodulated, deinterleaved and input to the RCPT decoder, where error correction is performed and the CRC coded sequence estimate $\{\hat{u}_k\}$ is obtained. If no error is detected, the CRC decoder outputs the received binary data sequence. In the case of errors being detected by the CRC decoder, a retransmission is requested.

Three signaling techniques considered in this paper are OFDM, multicode MC-CDMA, and multicode DS-CDMA. Figure 2 shows how N_c data-modulated symbols are adjusted in each of the three signaling techniques. Transmission of N_c data symbols is considered, where N_c denotes the number of subcarriers in OFDM and MC-CDMA. In all the schemes, N_c data-modulated symbols are transmitted over a timing interval of N_cT, where T is the data-modulated symbol length. However, time, frequency and code utilization differ among the schemes. Guard interval (GI) is necessary for OFDM and MC-CDMA, but is omitted in Fig. 2 for simplicity.

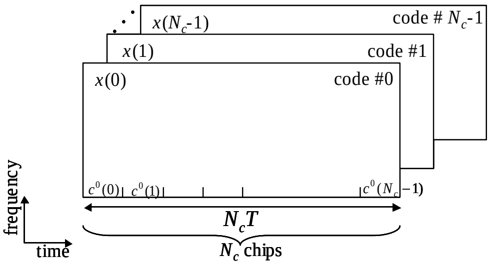
It is assumed that the spreading factors in MC-CDMA and DS-CDMA is the same as the number of subcarriers, i.e., N_c. The frequency domain minimum mean square error (MMSE) equalization is carried in MC-CDMA. An ideal rake receiver is assumed for DS-CDMA.



(a) OFDM



(b) MC-CDMA



(c) DS-CDMA

Figure 2. Time, frequency and code utilization.

3. RCPT HARQ

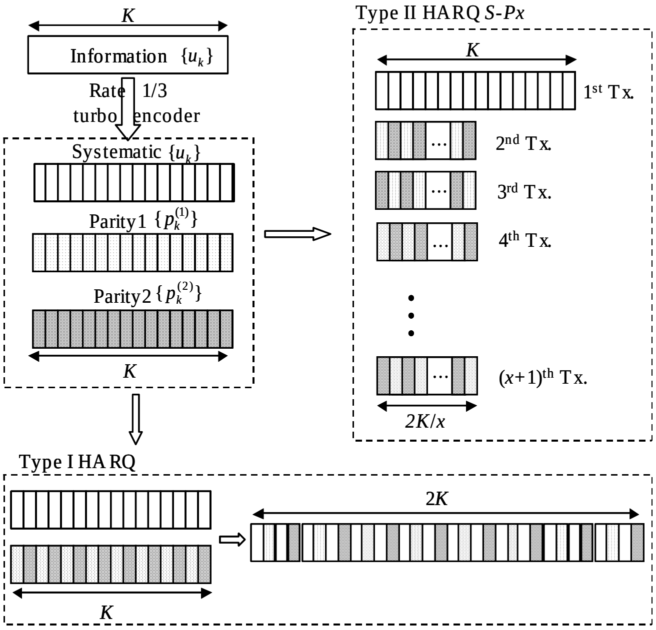


Figure 3. Different RCPT HARQ schemes.

Two types of HARQ schemes - type I and type II HARQ - are considered in this paper. The schematic diagrams are shown in Fig. 3. They are obtained by puncturing a rate 1/3 turbo code with different puncturing period P [5], [6]. The turbo encoder/decoder parameters are shown in Table 1.

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

(1) *Type I HARQ*: The two parity bit sequences $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$, obtained after rate 1/3 turbo coding are punctured with P=2 and transmitted along with the information sequence.

(2) *Type II HARQ*: Three type II HARQ schemes are considered, represented by *S-Px* (Systematic-Puncture period $P = x$). $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$ are punctured with P=x and x different sequences of length $2K/x$ are obtained, where K is the CRC encoded sequence length. The puncturing matrices for the different schemes are as follows:

Puncturing matrices for *S-P*2 (binary notation):

$$\begin{bmatrix}1&1\\0&0\\0&0\end{bmatrix}\begin{bmatrix}0&0\\1&0\\0&1\end{bmatrix}\begin{bmatrix}0&0\\0&1\\1&0\end{bmatrix}$$

Puncturing matrices for *S-P*4 (binary notation):

$$\begin{bmatrix}1&1&1&1\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\1&0&0&0\\0&0&1&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&1&0&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&0&1&0\\1&0&0&0\end{bmatrix}\begin{bmatrix}0&0&0&0\\0&0&0&1\\0&1&0&0\end{bmatrix}$$

Puncturing matrices for *S-P*8 (octal notation):

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

In all the schemes the first transmission consists of transmitting only the systematic bit sequence $\{u_k\}$ of length K. The number of bits transmitted in the second transmission onwards differs depending on the puncturing period. After each retransmission, turbo decoding is performed. As the number of retransmissions increases, the resultant code rate decreases. For *S-P*2, the systematic bit sequence and the two parity bit sequences are received after 3 transmissions, whereas it takes 5 and 9 transmissions for *S-P*4 and *S-P*8. In all the schemes, incremental redundancy and packet combing (in case the same packet is retransmitted) are utilized [5], [6].

4. Simulation Results

Table 2: Simulation conditions

Information sequence length	K=1024 bits	
Channel code	Rate 1/3 turbo code	
Channel interleaver	Block interleaver	
Data modulation	Coherent BPSK	
Signaling technique	Spreading code	Short orthogonal codes and a long PN code
	Multicode DS-CDMA	Spreading factor SF_{DS}=256
	OFDM/ Multicode MC-CDMA	No. of subcarriers N_c=256
		Effective symbol length T_s=256T_c
		GI : T_g=32T_c (T_g/T_s=1/8)
		Spreading factor SF_{MC} =256
Channel model	Data channel	Rayleigh fading (L=1~16) $\tau_l = lT_c$ $f_D(N_cT)$ = 0.001
	ARQ channel	Ideal
ARQ	Number of retransmissions	$\propto$
	Type	Basic, Type I, Type II

The 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 2^a x 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. Ideal coherent BPSK data modulation/demodulation is assumed. A long pseudo noise (PN) code with a period of 4095 chips is used as the scramble sequence for DS-CDMA, MC-CDMA and OFDM.

An exponential power delay profile with the number of propagation paths L=16 and the lth path time delay τ_l=lT_c is assumed. The maximum normalized Doppler frequency $f_D(N_cT)$

= 0.001 and the decay factor of the power delay profile α=0dB (uniform power delay profile) are assumed unless otherwise stated.

In the following simulations the information sequence length K = 1024bits (CRC encoded sequence length is treated as the information sequence length). The throughput efficiency η is defined as

$$\eta = \frac{\text{Number of information bits transmitted successfully}}{\text{Total number of bits transmitted}} \quad .(2)$$

An error-free reverse channel and ideal error detection are assumed. The number of retransmissions is taken to be infinite. Estimations of the channel gain, noise power density and the number of users are assumed to be ideal.

For multicode MC-CDMA and OFDM systems, we assume N_c = 256 subcarriers with a guard interval of $T_g = T_s/8$ (i.e., N_g = 32). IFFT and FFT sampling period $T_c = T_s/256$. The multicode MC-CDMA spreading factor SF_{MC}=256. For multicode DS-CDMA system we assume a spreading factor SF_{DS}=256 to ensure that the data rate is the same as that for MC-CDMA and OFDM. However due to the GI insertion needed for MC-CDMA and OFDM, the bandwidth is 9/8 times that of the DS-CDMA system. Ideal Rake combiner with the number of fingers equal to the number L of paths is assumed.

4.1. Different HARQ Schemes

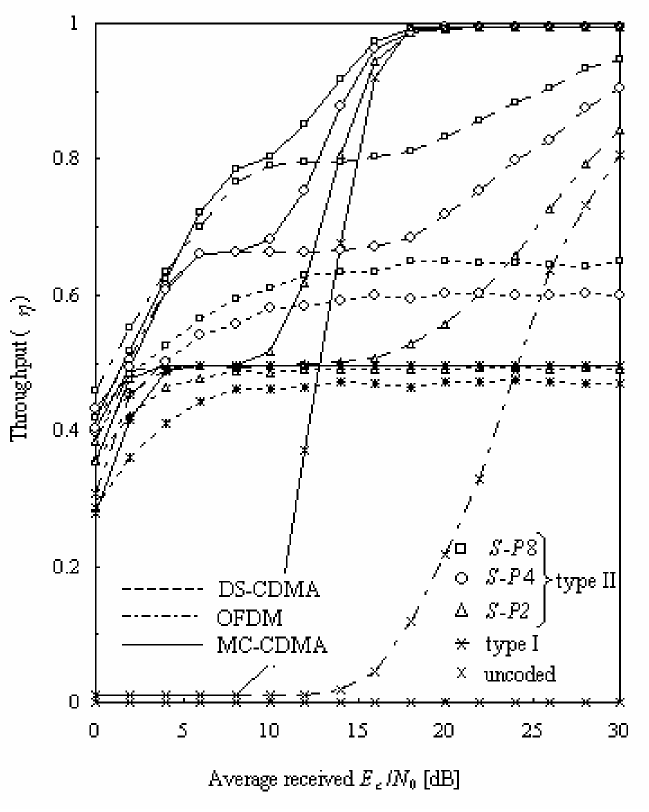


Figure 4. Throughput for different HARQ schemes.

The throughputs of the different HARQ schemes described in Section 4 are plotted as a function of the average received signal energy per coded bit to the AWGN power spectral density ratio (E_c/N_0) for the different signaling techniques in Fig. 4 when L=16 and α=0dB. Type I HARQ scheme has better throughput than when no coding is applied, however as the redundancy bits equal to the number of information bits are always transmitted the throughput is always less than 0.5. Among the type II HARQ schemes, the highest throughput is attained with the type II HARQ *S-P*8 scheme for all the signaling techniques. The number of bits transmitted in the second transmission onwards is less for the *S-P*8 scheme; the transmission of unnecessary redundant bits is avoided and the throughput is seen to be better than either the type II HARQ *S-P*2 or *S-P*4 scheme. For all the HARQ schemes, the throughput is the highest for multicode MC-CDMA and the worst for multicode DS-CDMA due to the frequency-selectivity of the channel. This is discussed in the next section.

4.2. Channel Selectivity

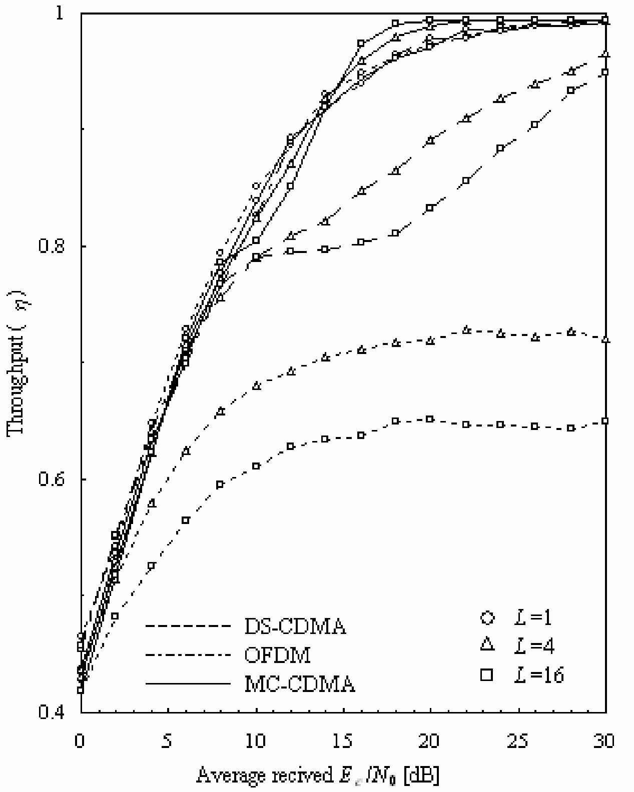


Figure 5. Throughput comparison with L as a parameter for type II HARQ *S-P*8.

Figure 5 plots the throughput as a function of the average received E_c/N_0 for the three different signaling schemes with the number L of paths as a parameter for type II HARQ *S-P*8 scheme. When L=1, the throughput for all the signaling techniques are seen to be similar with the throughput of OFDM and multicode MC-CDMA being only slightly inferior due to the guard interval penalty. On the other hand, when L increases to 4 and 16, the throughput of OFDM and multicode DS-CDMA decreases. In OFDM, the throughput decreases because of the higher frequency-selectivity of the channel which results in more random errors unsuitable for packet transmissions. For DS-CDMA the degradation is worse even with ideal rake combining. This is because of the orthogonality destruction resulting due to the existence of multiple strong paths. The throughput of multicode MC-CDMA remains almost unchanged. When L>1, the frequency-selectivity of the channel results in orthogonality destruction, however, frequency-domain MMSE equalization is applied at the receiver to partially restore the orthogonality. For type II HARQ S-P8 the average channel gain of all the data symbols in a packet is same as each data symbol is spread over all the subcarriers when $SF_{MC}=N_c$. Hence even with the change in L, the throughput remains almost unchanged.

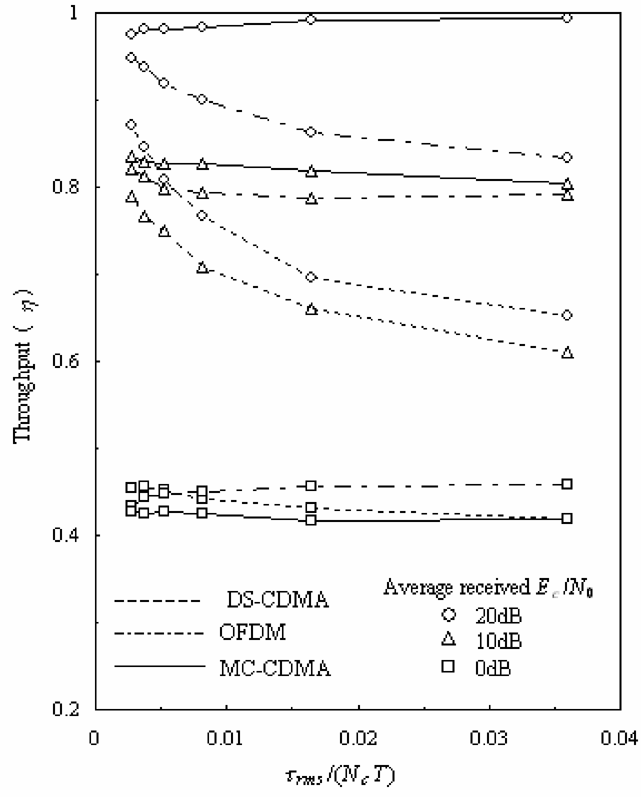


Figure 6. Throughput as a function of $\tau_{rms}/(N_cT)$ for type II HARQ S-P8.

The frequency-selectivity of the channel is often expressed in terms of the delay spread of the channel. The throughput is plotted as a function of the delay spread normalized by the signaling period, $\tau_{rms}/(N_cT)$, in Fig. 6. Note that, $N_cT=T_{OFDM}=T_{MC\text{-}CDMA}$. The delay spread $\tau_{rms}/(N_cT)$ is varied by changing the decay factor α of the power delay profile with L=16 and $\tau_l=lT_c$. As $\tau_{rms}/(N_cT)$ increases, the throughput for multicode DS-CDMA and OFDM decreases due to the increased frequency-selectivity. However the throughput for multicode MC-CDMA remains almost unchanged.

The normalized maximum Doppler frequency $f_D(N_cT)$ is the measure of the channel's time-selectivity. $f_D(N_cT)$ increases with the increase in the moving speed of the mobile or with the decrease in the data rate $1/T$, and vice versa ($f_D(N_cT)$=0.001 corresponds to the mobile terminal moving at a speed of 50 km/h at a carrier frequency of 2GHz and a data rate of 20Mbps). The effect of changing $f_D(N_cT)$ on the throughput of type II HARQ S-P8 is plotted in Fig. 7. The throughput is seen to be independent of the time-selectivity of the channel.

Comparison of Figs. 6 and 7 shows that the throughputs of DS-CDMA, MC-CDMA and OFDM are sensitive to the frequency-selectivity and not the time-selectivity of the channel.

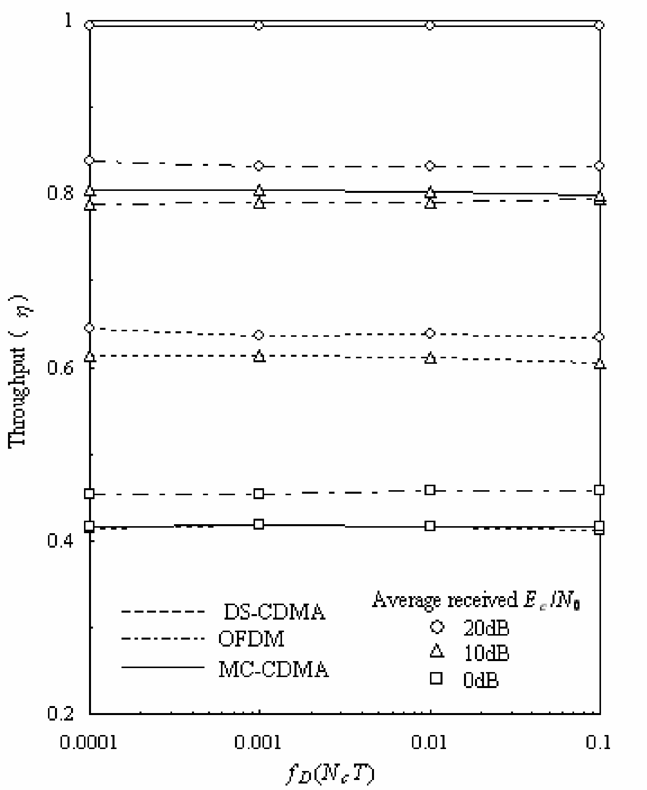


Figure 7. Throughput as a function of $f_D(N_cT)$ for type II HARQ S-P8.

4.3. Antenna Diversity Reception

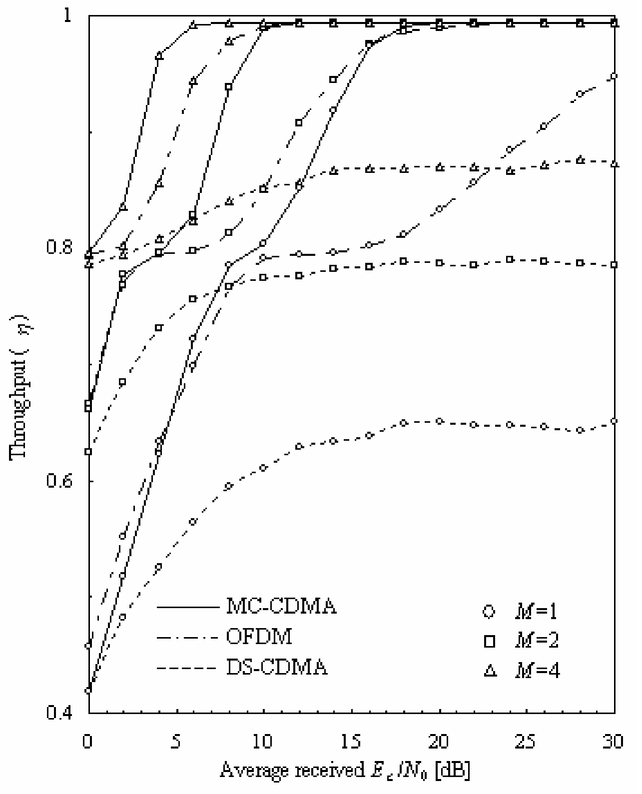


Figure 8. Throughput with receive antenna diversity for type II HARQ S-P8.

So far, we have considered a single antenna at the receiver. Recently using multiple antennas has been looked upon as a desirable technique to improve throughput [12]. Figure 8 plots the effect of using *M* antennas at the receiver. It is seen that as expected the throughput with antenna diversity can be significantly improved compared to that with no diversity. However, the additional performance improvement decreases with the increase in the number of antennas. With antenna diversity as well, the performance of multicode MC-CDMA is the best, followed by OFDM and then multicode DS-CDMA. Even for multicode DS-CDMA, the throughput performance improves as *M* increases, but never approaches unity.

5. Conclusion

Throughput performance comparison of OFDM, multicode MC-CDMA and multicode DS-CDMA was performed when RCPT HARQ is used for error control. It was found that in a frequency-selective fading channel the throughput of MC-CDMA is higher than that of either OFDM or DS-CDMA. The DS-CDMA throughput is worst in spite of ideal rake combining because of orthogonality destruction resulting due to the existence of multiple paths having different time delays. The OFDM throughput decreases due to increased random errors which are unsuitable for packet transmissions. The MC-CDMA throughput is not affected by the channel frequency-selectivity as a result of the frequency-domain MMSE equalization, which restores the orthogonality to a certain extent, and the spreading of each symbol over the entire subcarriers available. The throughput is not dependent on the channel time-selectivity. Using antenna diversity reception significantly improves the performance of all the schemes; however the additional improvement decreases as the number of antennas increases.

References

[1] F. Adachi, M. Sawahashi, and H. Suda, “Wideband DS-CDMA for next generation mobile communications systems,” IEEE Commun. Mag., vol. 36, pp. 56-69, Sept. 1998.

[2] R. Van Nee and R. Prasad, *OFDM for wireless multimedia communications*, Artech House, 2000.

[3] S. Hara and R. Prasad, “Overview of multicarrier CDMA,” IEEE Commun. Mag., pp.126-144, Dec. 1997.

[4] S. Hara and R. Prasad, “Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels,” IEEE Trans. Veh. Technol., Vol. 48, pp. 1584-1595, Sept. 1999.

[5] D. Garg and F. Adachi, “Throughput of RCPT hybrid ARQ for DS-CDMA with diversity reception and rake combining,” Proc. of VTC03 Spring, pp. 2730-2734, Korea, April 2003.

[6] D. Garg and F. Adachi, “Rate compatible punctured turbo-coded hybrid ARQ for OFDM in a frequency selective fading channel,” Proc. of VTC03 Spring, pp. 2725-2729, Korea, April 2003.

[7] F. Adachi, K. Ohono, A. Higuchi, T. Dohi and Y. Okumura, “Coherent multicode DS-CDMA mobile radio,” IEICE Trans. Commun., Vol. E79-B, No. 9, pp. 1316-1325, Sept. 1996.

[8] R. Kimura and F. Adachi, “Comparison of OFDM and multicode MC-CDMA in a frequency selective fading channel,” Electronics Letters, Vol. 39, pp. 317-318, Feb. 2003.

[9] D. Garg and F. Adachi, “On the spreading factor of multicode MC-CDMA with RCPT hybrid ARQ,” IEICE General Conf., B-5-49, Tohoku Univ., Sendai, Japan, March 2003.

[10] C. Kchao and G. L. Stuber, “Analysis of a direct-sequence spread-spectrum cellular radio system,” IEEE Trans. Commun., Vol. 41,pp. 1507-1516, Oct. 1993.

[11] F. Adachi, “Transmit power efficiency of fast transmit power controlled DS-CDMA reverse link,” IEICE Trans. Fundamen., Vol. E80-A, pp. 2420-2428, Dec. 1997.

[12] F. Adachi and T. Sao, “Joint antenna diversity and frequency-domain equalization for multi rate MC-CDMA,” IEICE Trans. Commun., to appear.