MC-CDMA HARQ with Variable Spreading Factor

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Abstract-**This paper presents a hybrid automatic repeat request (HARQ) with variable spreading factor (VSF) suitable for a multicarrer code division multiple access (MC-CDMA). We consider a HARQ based on incremental redundancy (IR) strategy. The throughput of MC-CDMA HARQ is a tradeoff among the frequency diversity gain, the coding gain and the inter-code interference (ICI). In order to effectively exploit the channel frequency-selectivity and the channel coding, the spreading factor is changed between the initial transmission and the succeeding retransmissions. The throughput performance of HARQ with VSF in a frequency-selective Rayleigh fading channel is evaluated by the computer simulation and compared with that with fixed spreading factor (FSF). It is shown that HARQ with VSF can provide better throughput performance than with FSF and is particularly useful when high-level modulation (e.g., 16QAM and 64QAM) is used. The impacts of fading correlation between packet retransmissions and the channel frequency-selectivity on achievable throughput performance are discussed.**

Keywords-MC-CDMA, HARQ, variable spreading factor

I. INTRODUCTION

Next generation mobile communications systems require a high-speed and high-quality packet transmission technique. Multicarrier code division multiple access (MC-CDMA) has been considered to be a promising wireless access in a severe frequency-selective fading channel [1]-[3]. An automatic repeat request (ARQ) combined with channel coding, called hybrid ARQ (HARQ) [4], is an inevitable technique, since error-free transmission must be guaranteed for packet data services. The throughput performance of MC-CDMA HARQ is a tradeoff among the frequency diversity gain, the coding gain and the inter-code interference (ICI) due to the orthogonality distortion [5]. As the spreading factor increases, the frequency diversity gain increases, but the coding gain decreases due to less frequency interleaving effect and the ICI gets stronger. Thus, the spreading factor plays an important role.

In this paper, we present a multicode MC-CDMA HARQ with variable spreading factor (VSF) for effectively exploiting the channel frequency-selectivity and the channel coding. We consider a HARQ based on incremental redundancy (IR) strategy [5]-[7] that gives higher throughput than a HARQ based on Chase combining strategy [8]. In IR-HARQ, uncoded information packet is transmitted first and then parity bit packet is transmitted if the first packet is received with error. Since the first packet is uncoded, only the frequency diversity gain is expected. However, in the second transmission onwards, parity bit packet is transmitted and thus the coding gain is obtained. Hence, the spreading factor should be optimized for the first transmission and second transmission onwards differentially. Simulation results show that the HARQ with VSF provides better throughput performance than with fixed spreading factor (FSF) and is particularly useful when high-level modulation of 16QAM and 64QAM is used.

In a HARQ, there exists the round-trip delay [9], which consists of the transmission delay and the processing delay both at the transmitter and at the receiver. As the fading correlation between adjacent packet transmissions depends on the round-trip delay and the terminal moving speed, it affects the throughput of HARQ. Hence, the impact of the fading correlation in addition to the channel frequency-selectivity is discussed.

The remainder of the paper is organized as follows. Sect. 2 describes the transmission system model of MC-CDMA HARQ with VSF. Sect. 3 optimizes the spreading factor used in each packet transmission. In Sect. 4, the simulated throughput performance of HARQ with VSF is compared with that with FSF and the impacts of the fading correlation and the channel frequency-selectivity are discussed. Section 5 concludes the paper.

II. TRANSMISSION SYSTEM MODEL

The MC-CDMA HARQ transmission system model is illustrated in Fig. 1. We consider a multicode MC-CDMA with N_c subcarriers. The spreading factor SF_i is used at the i-th (i=0, 1, 2,$\cdots$) packet transmission. The code-multiplexing order at the i-th transmission is denoted by C_i. We assume full code multiplexing (i.e., C_i=SF_i) and thus the transmission symbol rate is the same as in orthogonal frequency division multiplexing (OFDM); a total of SF_i data symbols are transmitted in parallel over SF_i subcarriers.

At a transmitter, a cyclic redundancy check (CRC) coded sequence (we consider this sequence as the information sequence) is input to the turbo encoder and the turbo encoded sequences (i.e., a systematic (or information) bit sequence and two parity bit sequences) are stored in the buffer for transmissions. The systematic bit sequence and punctured parity bit sequences are block-interleaved and data-modulated. The data-modulated symbol sequence is serial-to-parallel (S/P) converted to C_i streams $\{d_c(n); c=0\sim C_i-1, n=0\sim N_c/SF_i-1\}$. Then, C_i streams are spread using the orthogonal spreading codes $\{c_c^{oc}(k); c=0\sim C_i-1, k=0\sim SF_i-1\}$, where $\left|c_c^{oc}(k)\right|=1$, and then code-multiplexed. Finally, a long scramble sequence $\{c_{scr}(k); k=0\sim N_c-1\}$ is multiplied. Then, N_c-

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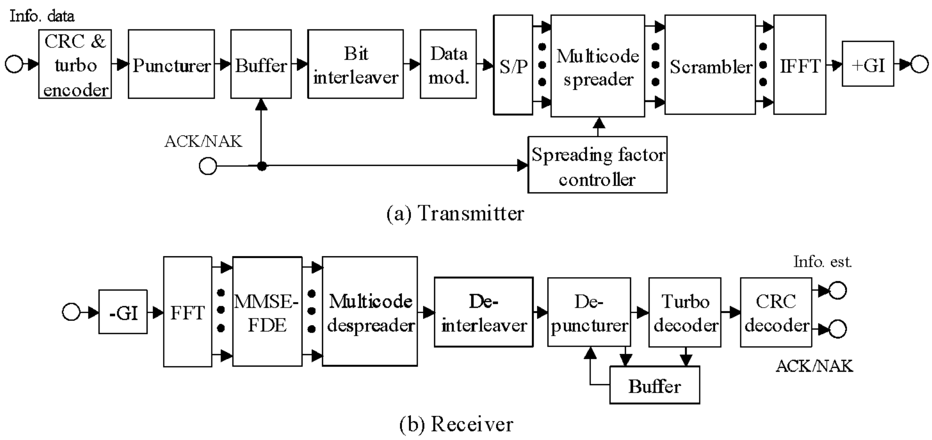


Fig. 1 MC-CDMA HARQ transmission system model.

point inverse fast Fourier transform (IFFT) is applied to generate a multicode MC-CDMA packet signal having N_c subcarriers. The k-th subcarrier component $S(i,k)$, k=0~N_c-1, is expressed as

$$S(i,k)=\sqrt{\frac{2P}{SF_i}}\sum_{c=0}^{C_i-1} d_c(\lfloor k/SF_i \rfloor)c_c^{oc}(k \bmod SF_i)c_{scr}(k)\,, \quad (1)$$

where P represents the transmit power and $\lfloor x \rfloor$ is the largest integer smaller than or equal to x. After the insertion of an N_g-sample guard interval (GI), the resultant multicode MC-CDMA packet signal is transmitted over a frequency-selective fading channel.

An L-path block-fading channel is assumed (i.e., the fading channel gain does not change during one packet transmission interval). The impulse response $h(i,\tau)$ of the multipath channel at the i-th packet transmission may be expressed as

$$h(i,\tau)=\sum_{l=0}^{L-1} h_l(i)\delta(\tau-\tau_l) \quad (2)$$

with $\sum_{l=0}^{L-1} E[|h_l(i)|^2]=1$, where $\delta(t)$ is the delta function and $E[.]$ denotes ensemble average operation. $h_l(i)$ and τ_l are respectively the path gain and the time delay of the l-th path. According to the mobile terminal movement, $h_l(i)$ varies.

The received multicode MC-CDMA packet signal is perturbed by the additive Gaussian noise (AWGN). The N_g-sample GI is removed first and the N_c-point FFT is applied to decompose the received packet signal into the N_c-subcarrer components $\{R(i,k);\ k$=0~N_c-1$\}$. The k-th frequency component is expressed as

$$R(i,k)=S(i,k)H(i,k)+N(i,k)\,, \quad (3)$$

where $H(i,k)$ and $N(i,k)$ are the channel gain and the noise component at the k-th subcarrier in the i-th packet reception. $H(i,k)$ is given by

$$H(i,k)=\sum_{l=0}^{L-1} h_l(i)\exp(-2\pi k\tau_l/N_c)\,. \quad (4)$$

Minimum mean square error (MMSE) based frequency-domain equalization (FDE) is performed, followed by multicode despreading. The decision variable for the data symbol $d_c(n)$ can be expressed as

$$\hat{d}_c(n)=\frac{1}{SF_i}\sum_{k=nSF_i}^{(n+1)SF_i-1} R(i,k)w(i,k)\{c_c^{oc}(k \bmod SF_i)c_{scr}(k)\}^*\,, \quad (5)$$

where $w(i,k)$ is the MMSE-FDE weight. Since C_i=SF_i, $w(i,k)$ is given by [3]

$$w(i,k)=\frac{H^*(i,k)}{|H(i,k)|^2+\sigma^2}\,, \quad (6)$$

where $2\sigma^2$ is the variance of the AWGN. Following the same procedure as in [10] but with SF_i, the log-likelihood ratio (LLR) is computed. Then, the resulting LLR sequence is de-interleaved, de-punctured and input into the turbo decoder.

III. Optimization of SF_i

The HARQ considered in this paper is obtained from the rate 1/3 turbo code. A rate 1/3 turbo encoder produces a systematic bit (information bit) sequence and two parity bit sequences. The three sequences are punctured according to puncturing matrices $\{P_i\}$ for the i-th packet transmission as follows [5]:

$$P_0=\begin{bmatrix}1 & 1\\ 0 & 0\\ 0 & 0\end{bmatrix},\quad P_1=\begin{bmatrix}0 & 0\\ 1 & 0\\ 0 & 1\end{bmatrix},\quad P_2=\begin{bmatrix}0 & 0\\ 0 & 1\\ 1 & 0\end{bmatrix}, \quad (7)$$

where the first row corresponds to the information bit sequence and the 2nd and 3rd rows correspond to the parity bit sequences. “0” means the deletion of the bit at the corresponding position. At the first transmission (i=0), only the information packet is transmitted. If packet error is detected, the 2nd transmission (i=1) is requested; the parity bit packet is transmitted for turbo decoding. If packet error is still detected, the different parity bit packet is transmitted at the 3rd transmission (i=2). As the number of retransmissions increases, the resultant code rate decreases and thus, the coding gain increases.

The throughput of MC-CDMA HARQ is determined by the tradeoff between the frequency diversity gain, the coding gain and the ICI due to the orthogonality distortion. The ICI increases with increase in the spreading factor SF_i since the code-multiplexing order C_i increases when C_i=SF_i. In the HARQ with VSF, the spreading factor at the first transmission (i=0) is set to be the largest possible, i.e., SF_0=N_c, so that the largest frequency diversity gain can be achieved (the degradation due to the ICI can be offset by the diversity gain). In each retransmission (i≥1), the coding gain owing to the turbo decoding is obtained besides the frequency diversity gain. By computer simulation, we found that SF_i=1 for i=1, 2, 3,··· provides the best throughput.

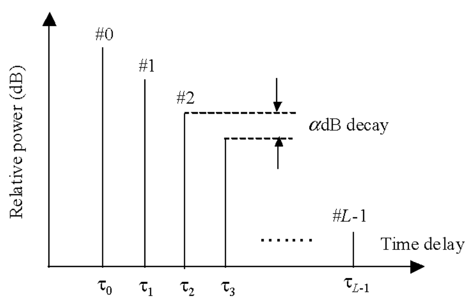


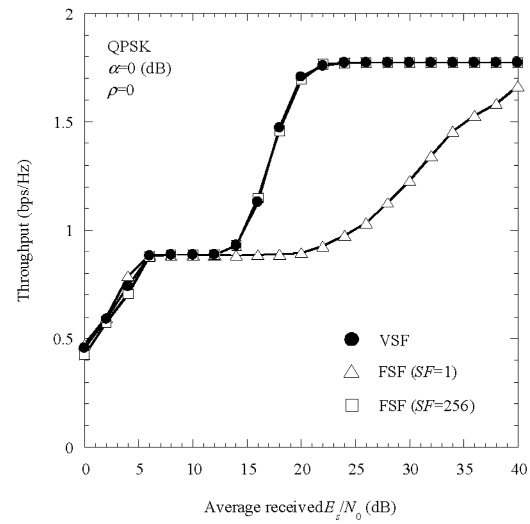
Fig. 2 Exponential power delay profile.

IV. SIMULATION RESULT

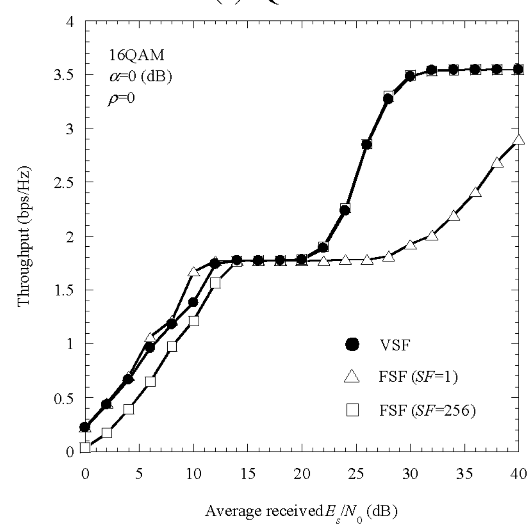
The throughput performance of the multicode MC-CDMA HARQ with VSF is evaluated by computer simulation. The number of subcarriers and the GI length are respectively N_c=256 and N_g=32. Maximum number of retransmissions is assumed to be infinite. A rate-1/3 turbo code having constraint length 4 and two (13, 15) recursive systematic component encoders is used. The information sequence length K is assumed to be K=2048 bits and 64x32 channel block-interleaver is used. QPSK, 16QAM and 64QAM data-modulation are considered. We consider a frequency-selective Rayleigh fading channel having a 16-path exponentially decaying power delay profile with decay factor of αdB and a time-delay spacing of 1 FFT sample, as shown in Fig. 2. At the receiver, Log-MAP decoding with 8 iterations is carried out. Perfect error detection is assumed. In the following, throughput (bit per second per Hertz) is defined as

$$\eta = B \times \frac{N_{suc}}{N_{total}} \times \frac{N_c}{N_c + N_g}, \quad (8)$$

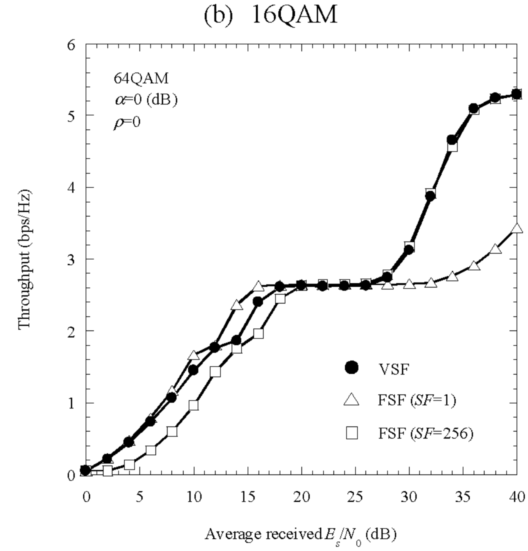
where B denotes the number of bits for QPSK, 16QAM and 64QAM. N_{total} and N_{suc} are the total number of transmitted bits and successfully received information bits, respectively.



(a) QPSK



(b) 16QAM



(c) 64QAM

Fig. 3 Throughput performance comparison.

A. *Throughput performance comparison*

The simulated throughput performance of multicode MC-CDMA HARQ with VSF is plotted as a function of the average received symbol energy-to-the AWGN power spectrum density ratio (E_s/N_0) in Fig. 3 when ρ=0. The uniform power delay profile (i.e., α=0dB) is assumed. For comparison, throughput curves with FSF of SF=256 (C=256) and SF=1 (C=1) that show the lower- or upper-bounded performance [5] are also plotted. It is seen from Fig. 3 that for HARQ with FSF, the use of SF=256 (1) attains the best throughput in a high (low) E_s/N_0 region. The reason for this is explained below. Since the use of larger spreading factor increases the probability of the first packet being correctly received due to the larger frequency diversity gain, SF=256 is the optimum in a high E_s/N_0 region. On the other hand, in a low E_s/N_0 region, since two or more retransmissions are always necessary, SF=1 provides the largest coding gain due to frequency interleaving effect and then achieves the best throughput. However, it is seen from the figure that the HARQ with VSF offers almost the best throughput performance over a wide range of E_s/N_0 and is especially useful when the high-level modulation (e.g., 16QAM and 64QAM) used.

B. *Impact of fading correlation*

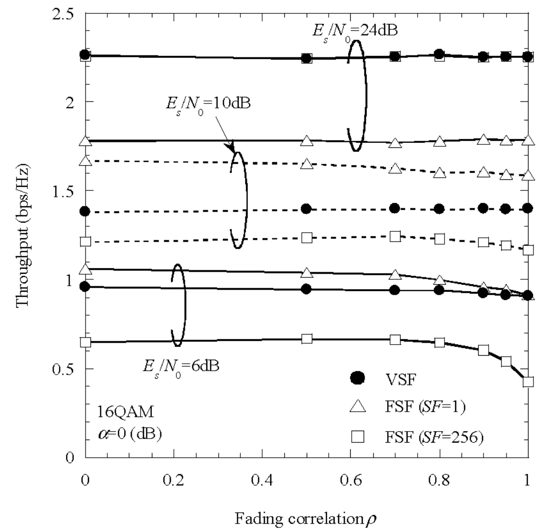
Since the time diversity effect in a HARQ is related to the fading correlation between adjacent packet transmissions, the dependency of the throughputs of HARQ with VSF and with FSF on the fading correlation is discussed in this subsection. Assuming the Jakes fading model [11], the fading correlation between adjacent packet transmissions is given as

$$\rho = \frac{E[h_l^*(i)h_l(i+1)]}{\sqrt{E[|h_l(i)|^2]}\sqrt{E[|h_l(i+1)|^2]}} = J_0(2\pi f_D T_{rd}), \quad (9)$$

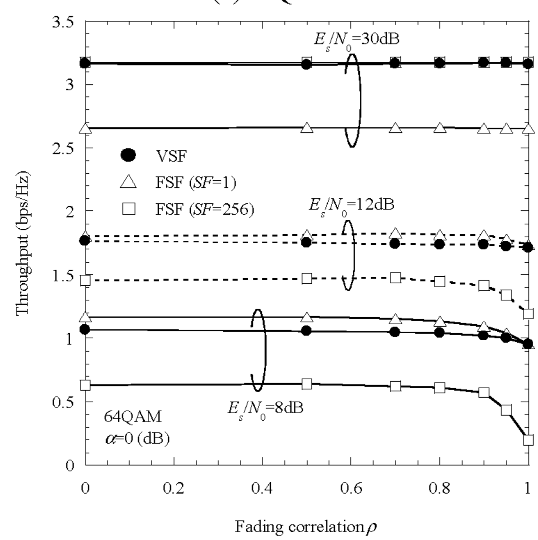
where * denotes the complex conjugate operation and $J_0(2\pi f_D T_{rd})$ is the zero-th order Bessel function of first kind with f_D and T_{rd} representing the maximum Doppler frequency and the round-trip delay, respectively.

Figure 4 plots the throughput as a function of the fading correlation ρ for various average E_s/N_0 when α=0dB. For high E_s/N_0, where the probability of the first packet being correctly received is high, the throughput is almost insensitive to the fading correlation. However, for low E_s/N_0, the two or more retransmissions are always required and thus throughput depends on ρ. It is seen that almost the same throughput can be obtained if ρ<0.8 (which approximately corresponds to $f_D T_{rd}$>0.145).

Figure 4 also indicates that HARQ with FSF is more sensitive to ρ, especially in the case of SF=256. The throughput of HARQ with FSF degrades quickly as ρ increases beyond 0.8. This is explained as follows. In HARQ with FSF, when ρ is close to one, the LLR values of information bits transmitted at the first transmission are highly correlated to those of the parity bits transmitted at succeeding retransmissions. On the other hand, since the spreading factor is changed between the initial transmission and the succeeding retransmissions in HARQ with VSF, LLR values for information bits and parity bits are different. This has a similar effect to the interleaving and can reduce the throughput dependency on the fading correlation. Therefore, the introduction of VSF into HARQ can improve the robustness against the fading correlation.



(a) 16QAM

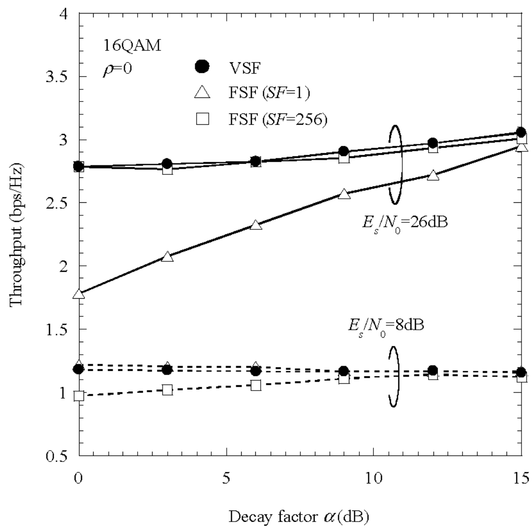


(b) 64QAM

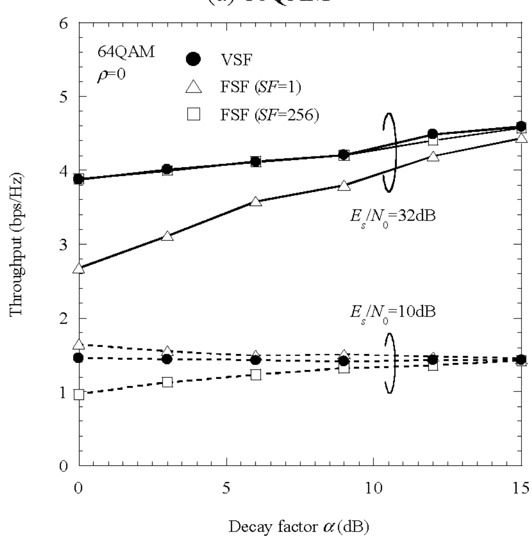
Fig. 4 Impact of fading correlation.

C. *Impact of channel frequency-selectivity*

The impact of the channel frequency-selectivity on the achievable throughput performance is investigated. The frequency-selectivity of the channel is related to the decay factor of power delay profile. Figure 5 plots the throughput as a function of decay factor α for 16QAM and 64QAM when ρ=0. 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 the throughputs of both FSF and VSF improve as α increases (i.e., the frequency selectivity becomes weaker). Since the fading experienced by all the subcarriers becomes similar as α increases, the burst error tends to be produced which is desirable for ARQ protocol, resulting in the throughput improvement. For very large α, the performance is almost identical; however for lower α, VSF shows almost the best throughput both at low and high average E_s/N_0 values. Hence, it is concluded that irrespective of the channel frequency-selectivity, VSF provides almost the best throughput.



(a) 16QAM



(b) 64QAM

Fig. 5 Impact of channel frequency-selectivity.

V. CONCLUSION

In this paper, we presented HARQ with VSF to effectively exploit the channel frequency-selectivity and the channel coding for multicode MC-CDMA. The achievable throughput performance of HARQ with VSF in a frequency-selective Rayleigh fading channel was evaluated by the computer simulation and compared with that with FSF. The impacts of fading correlation and channel frequency-selectivity were also discussed. It was found from simulation results that the HARQ with VSF provides better throughput performance than with FSF and is particularly useful when high-level modulation of 16QAM and 64QAM is used. Also, we found that the use of VSF can reduce the throughput dependency on the fading correlation and provides almost the best throughput irrespective of the channel frequency-selectivity. It should be noted that the received E_s/N_0 measurement is not necessary for changing the spreading factor in HARQ with VSF.

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