LETTER

Frequency-Domain Rake Combining for Antenna Diversity Reception of DS-CDMA Signals

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SUMMARY Frequency-domain representation of the well-known time-domain rake combining for the antenna diversity reception of DS-CDMA signals is derived. Two receiver structures using frequency-domain rake combining are presented. Frequency-domain rake combining can alleviate the complexity problem of the time-domain rake arising from too many paths in a severe frequency selective fading channel at the cost of guard interval insertion. The results shown in this paper show a possibility that a DS-CDMA approach still remain to be promising for broadband wireless access technique.
key words: *frequency-domain equalization, rake combining, antenna diversity reception, DS-CDMA*

1. Introduction

Frequency selective multipath fading, encountered in a mobile wireless digital communication system, severely degrades the bit error rate (BER) performance [1]. In direct sequence code division multiple access (DS-CDMA), well-known time-domain rake combining is applied to exploit the frequency selectivity of the channel and to improve the BER performance [2]. Combined use of antenna diversity reception and rake combining can further reduce the effect of multipath fading. Increasing the spreading chip rate improves the multipath resolution capability [3]. However, if the spreading chip rate becomes too high (or the transmission bandwidth becomes broader), serious problems arise in time-domain rake combining. As the spreading chip rate becomes higher, the number of resolvable propagation paths increases. A large number of rake fingers are necessary for collecting enough signal power and this increases the complexity of the time-domain rake receiver. Rake combining needs accurate channel estimation of each path. However, as the spreading chip rate becomes higher, each propagation path becomes weaker and weaker and this makes accurate channel estimation more difficult. Because of these, DS-CDMA has not been considered as a strong candidate for broadband wireless systems and much attention has been paid to multicarrier CDMA (MC-CDMA) [4]–[8]. MC-CDMA uses frequency-domain spreading and despreading to exploit the multipath channel frequency selectivity while DS-CDMA uses time-domain spreading and despreading. MC-CDMA can achieve a good BER performance by using simple one-tap equalization on each frequency component. Meanwhile, frequency-domain equalization has been recently attracting much attention for single carrier wireless transmission systems [9]. This can also be applied to DS-CDMA signal reception.

In this paper, frequency-domain representation of the well-known time-domain rake combining for the antenna diversity reception of DS-CDMA signals is derived and two receiver structures using frequency-domain rake combining are presented. The achievable BER performances using time-domain and frequency-domain rake combining with antenna diversity reception in a frequency selective Rayleigh fading channel are evaluated by computer simulation and are compared.

2. Frequency-Domain Representation for Time-Domain Rake Combining

The discrete time representation is used throughout the paper. The DS-CDMA signal at the ith chip time instance may be expressed as

$$s(i) = \sqrt{2E_s/(SF \cdot T_c)}c(i)\sum_{k=-\infty}^{\infty} d_k u(i - k \cdot SF), \tag{1}$$

where E_s denotes the transmit data symbol energy, SF the spreading factor, T_c the spreading chip period, $c(i)$ the ith spreading chip with $|c(i)| = 1$, d_k the kth data symbol with $|d_k| = 1$, and $u(i) = 1$ (0) for $0 \le i < SF$ (otherwise). The DS-CDMA signal is transmitted over a frequency selective fading channel and received by M antennas. The channel is assumed to have L independent propagation paths, for which the chip-spaced time delay model is adopted. Without loss of generality, the time delay of the lth path is assumed to be $\tau_l = lT_c$, $l = 0 \sim L-1$. The DS-CDMA signal received on each antenna is filtered by a chip-matched filter and then sampled at the chip rate. Assuming a single user case, the signal sample received on the mth antenna ($m = 0 \sim M-1$) at time i may be represented in the equivalent lowpass representation as

$$r_m(i) = \sum_{l=0}^{L-1} \xi_{m,l}(i)s(i-l) + \eta_m(i), \tag{2}$$

where $\xi_{m,l}(i)$ is the complex-valued path gain of the lth

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propagation path and $\eta_m(i)$ is the zero-mean noise process due to the additive white Gaussian noise (AWGN) having a variance of $2(N_0/T_c)$ with N_0 being the one-sided AWGN power spectrum density. For simplicity, we assume very slow fading and the path gains remain constant over the data symbol period, i.e., $\xi_{m,l}(i) = \xi_{m,l,k}$ for $i = kSF \sim (k+1)SF-1$.

The time-domain rake combiner consists of L rake fingers per antenna, each taking the correlation between $\{r_m(i)\}$ and the delayed replica of the spreading chip sequence $\{c(i)\}$. A total of $M \times L$ rake finger outputs are then coherently combined. Thus, the time-domain rake combiner output $\hat{d}_k$ with M-branch antenna diversity reception, which is the decision variable for the kth transmitted data symbol, can be expressed as

$$\hat{d}_k=\sum_{m=0}^{M-1}\sum_{l=0}^{L-1}\xi^*_{m,l,k}\left(\frac{1}{SF}\sum_{i=kSF}^{(k+1)SF-1}r_m(i+l)c^*(i)\right), \tag{3}$$

where $(.)^*$ denotes the complex conjugate operation. Let $\{C_k(n)\}$ and $\{R_{m,k}(n)\}$ be the SF-point fast Fourier transforms (FFTs) of $\{c(i)\}$ and $\{r_m(i)\}$, respectively, for the kth data symbol period. A frequency-domain representation of Eq. (3) is given by

$$\hat{d}_k=\frac{1}{SF}\sum_{n=0}^{SF-1}C^*_k(n)\left(\frac{1}{SF}\sum_{m=0}^{M-1}R_{m,k}(n)w_{m,k}(n)\right), \tag{4}$$

where

$$\begin{cases} R_{m,k}(n)=\displaystyle\sum_{i=0}^{SF-1}r_m(i+kSF)\exp\left(-j2\pi n\frac{i}{SF}\right) \\ C_k(n)=\displaystyle\sum_{i=0}^{SF-1}c(i+kSF)\exp\left(-j2\pi n\frac{i}{SF}\right) \end{cases} \tag{5}$$

and $w_{m,k}(n)$ is the combining weight given by

$$w_{m,k}(n)=H^*_{m,k}(n) \tag{6}$$

with

$$H_{m,k}(n)=\sum_{l=0}^{L-1}\xi_{m,l,k}\exp\left(-j2\pi l\frac{n}{SF}\right) \tag{7}$$

being the transfer function of the propagation channel at time i=kSF. Since $\{C_k(n)\}$ can be viewed as the spreading chip sequence in the frequency-domain, Eq. (4) is equivalent to the MC-CDMA despreading process using simple one-tap equalization based on maximal ratio combining (MRC) [1]. Also applied is MRC-based antenna diversity reception on each frequency component.

An alternative expression for Eq. (4) can be obtained as

$$\hat{d}_k=\frac{1}{SF}\sum_{i=0}^{SF-1}c^*(i+kSF)\left(\sum_{m=0}^{M-1}\tilde{r}_{m,k}(i)\right), \tag{8}$$

where $\tilde{r}_{m,k}(i)$ is the SF-point inverse FFT (IFFT) of $\{R_{m,k}(n)H^*_{m,k}(n)\}$ and is given by

$$\tilde{r}_{m,k}(i)=\frac{1}{SF}\sum_{n=0}^{SF-1}R_{m,k}(n)H^*_{m,k}(n)\exp\left(j2\pi n\frac{i}{SF}\right). \tag{9}$$

Equations (4) and (8) represent corresponding frequency-domain rake combining while Eq. (3) represents time-domain rake combining.

When frequency-domain rake is used, the guard interval (GI) must be inserted in the transmitted spread signal sample sequence to make the received spread signal appear to be periodic with a period of SF samples, similarly to MC-CDMA. A cyclic prefix of Ng samples is inserted as GI at the beginning of each spread signal, as shown in Fig. 1. GI is designed to be larger than the maximum time delay difference among propagation paths. Assuming insertion of N_g-sample GI, the data transmission rate is reduced by a factor of $1+N_g/SF$ for the same chip rate and a power penalty of $10\log_{10}(1+N_g/SF)$ dB results. However, since frequency-domain rake combining applies simple one-tap frequency-domain equalization on each frequency component, it can alleviate the complexity problem of the time-domain rake arising from too many paths in a severe frequency selective fading channel at the cost of GI insertion.

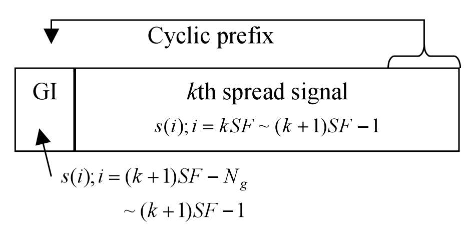
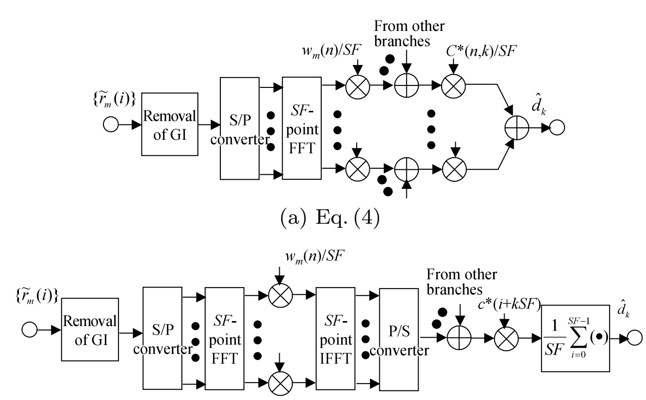


Fig. 1 Transmitted spread signal with guard interval insertion.



(a) Eq. (4)

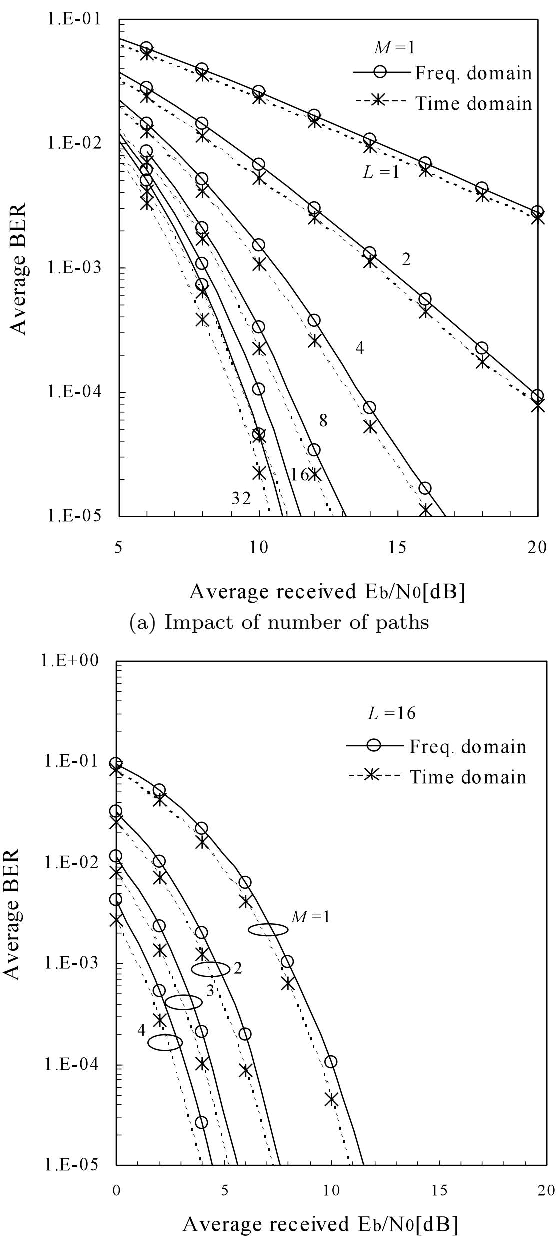
(b) Eq. (8)

Fig. 2 Frequency-domain rake receiver.

Two receiver structures using frequency-domain rake combining with antenna diversity reception are illustrated in Fig. 2. Frequency-domain rake combining based on Eq. (8) involves *SF*-point FFT and IFFT operations, while that of Eq. (4) involves FFT operation only.

3. Computer Simulation

It is assumed that the spreading factor SF=256 and the GI of N_g=32 samples. Quadrature phase shift keying (QPSK) data modulation is used. The spreading chip sequence is the M-sequence of 4095 chips. The fading channel is a very slow L-path frequency selective Rayleigh fading channel with uniform power delay profile. For performance comparison, time-domain rake combining is also considered. As stated earlier, the transmission data rate with frequency-domain rake combining is 9/8 times lower than the case with time-domain rake combining for the same chip rate. Channel estimation for frequency-domain and time-domain rake combining is assumed to be ideal. The simulated average BER performances are plotted in Fig. 3 as a function of the average received signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 (=$0.5E_s/N_0$ for QPSK). Figure 3(a) shows how the BER performance improves as the number L of paths increases for the no diversity reception case (M=1). As was theoretically predicted, frequency-domain rake combining can achieve the performance similar to time-domain rake combining. Slight performance degradation observed is attributed to the power penalty of 0.5 dB due to GI insertion. Figure 3(b) compares how antenna diversity reception improves the BER performance when L=16. Again, it is seen that frequency-domain rake combining can achieve a similar performance as time-domain rake combining.



(a) Impact of number of paths

(b) Impact of antenna diversity

Fig. 3 BER performance comparison.

4. Conclusion

We have developed frequency-domain representation of the well-known time-domain rake combining for the antenna diversity reception of DS-CDMA signals and suggested two receiver structures using frequency-domain rake combining. Frequency-domain rake combining applies FFT processing and uses simple one-tap equalization on each frequency component; thus, it can alleviate the complexity problem of the time-domain rake arising from too many paths in a severe frequency selective fading channel at the cost of GI insertion. It was confirmed by computer simulation that frequency-domain rake combining achieves an average BER performance similar to time-domain rake combining. The results shown in this paper have shown a possibility that a DS-CDMA approach still remain to be promising for broadband wireless access technique.

In this paper, ideal channel estimation was assumed. Both frequency-domain and time-domain rake combining require accurate channel estimation. In time-domain rake combining, as the number of paths increases, the received signal power of each path becomes weaker and weaker and this makes accurate channel estimation more difficult. On the other hand, in frequency-domain rake combining, the channel transfer function rapidly varying in the frequency-domain must be estimated. When practical channel estimation method is used, the achievable BER performances with frequency-domain and time-domain rake combining may be affected differently. Comparison of frequency-domain and time-domain rake combining using practical channel estimation is left as an interesting future study.

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