Performance of Multirate Transmission Schemes for a Multicarrier DS/CDMA System

Kang Soo Lim and Jae Hong Lee
School of Electrical Engineering, Seoul National University
Shillim-dong, Kwanak-gu, Seoul 151-742, Korea
Fax: +82-2-882-4657
E-mail: sooji2@snu.ac.kr

Abstract - In this paper, two multirate transmission schemes are considered for an asynchronous multicarrier (MC) DS/CDMA system: multicode scheme and multiple processing gain (MPG) scheme. Successive interference canceller (SIC) is applied for the two multirate MC-DS/CDMA systems to cancel multiple access interference (MAI). The bit error rate (BER) of each system is obtained by analysis and simulation in a Rayleigh fading channel with perfect channel estimation. It is shown that higher rate users have smaller BER than lower rate users in both systems. It is shown that the system with multicode scheme has better performance than the system with MPG scheme for high processing gain. Also it is shown that the former has even better performance than the latter when SIC is applied.

1. INTRODUCTION

Wireless communications will support various multimedia services such as voice, data and video which require multirate transmission and large bandwidth [1-2]. The multicode scheme and the multiple processing gain (MPG) scheme [3] are used to support multirate transmission in a DS/CDMA system. In the multicode scheme, the number of spreading codes assigned to a user varies according to data rate. In the MPG scheme, processing gain varies from user to user while chip rate is fixed.

As the total transmission bandwidth becomes wider, a single-carrier DS/CDMA system suffers from severer interchip interference (ICI). Also, a single-carrier wideband DS/CDMA system has difficulties in obtaining synchronization for a high-rate spreading sequence. A multicarrier (MC) DS/CDMA system which transmits identical information through multiple subcarriers experiences less ICI than a single-carrier DS/CDMA system having the same transmission bandwidth. Moreover, it is robust to narrowband interference as well as frequency-selective fading [4].

In this paper, the multicode scheme and the MPG scheme are considered for an asynchronous MC-DS/CDMA system. The bit error rate (BER) of each multirate MC-DS/CDMA system is obtained by analysis and simulation in a frequency-selective Rayleigh fading channel [5] with perfect channel estimation. Successive interference canceller (SIC) is applied for the multirate MC-DS/CDMA systems to mitigate the effect of multiple access interference (MAI) [6].

The rest of this paper is organized as follows. In section II, two multirate MC-DS/CDMA systems are described. In section III, the system performance is analyzed for a frequency-selective Rayleigh fading channel. In section IV, SIC for the multirate MC-DS/CDMA system is described. In section V, the simulation results are shown and the conclusions are drawn in section VI.

2. MULTIRATE MC-DS/CDMA SYSTEMS

Consider an asynchronous multirate MC-DS/CDMA system with BPSK modulation and constant chip duration $T_c$. An MC-DS/CDMA system transmits identical information through $M$ subcarriers. Suppose that the subcarrier bandwidth is less than the coherence bandwidth of the channel so that the fading over each subcarrier is frequency-nonselective. Suppose that multirate users are classified into $n$ groups with different data rates. Let the number of users and the transmission rate of a user in the group $i$ be denoted by $K_i$ and $R_i$, $i=0,1,\ldots,n-1$, respectively. Assume that $R_i=l_iR_0$, $i=0,1,\ldots,n-1$, with restriction that $1=L_0<L_1<\ldots<L_{n-1}$ and $L_i$ divides $L_{i-1}$. During the bit duration of a group 0 user $T_0$, a group $i$ user transmits $L_i$ bits with bit duration $T_i=T_0/L_i$.

2.1 MC-DS/CDMA System with Multicode Scheme

The block diagram of the MC-DS/CDMA system with the multicode scheme is shown in Fig. 1. Fig. 1(a) shows the transmitter of the MC-DS/CDMA system with the multicode scheme. A group $i$ user has $L_i$ spreading codes to transmit $L_i$ bits during the bit duration of a group 0 user $T_0$. The $L_i$ bits of a group $i$ user are serial-to-parallel converted and spread by $L_i$ spreading codes. All users have same processing gain $N=T_0/T_c$ regardless of data rate. The $l$-th spreading code of the user $k$ in the group...
system with the multicode scheme. The received signal at the receiver is given by

\[ r(t) = \sqrt{2} \sum_{m=0}^{M-1} \sum_{n=0}^{K-1} \alpha_{i,k}^{(m)}(t - \tau_{i,k}) \cos(2\pi f_n t + \theta_{i,k}^{(m)}) + n(t) \]  

(3)

where \( \tau_{i,k} \) is the time delay of the user \( k \) in the group \( i \), \( f_n \) is the center frequency of the \( m \)-th subcarrier, \( \alpha_{i,k}^{(m)} \) is the Rayleigh-distributed fade envelope and \( \theta_{i,k}^{(m)} \) is the phase uniformly distributed over \([0, 2\pi]\) for the \( m \)-th subcarrier of the user \( k \) in the group \( i \). The received signals over all subcarriers are down-converted and despread by the \( L_i \) spreading codes of the desired user. For the user \( k \) in the group \( i \), the decision statistic for the \( l \)-th bit over the \( m \)-th subcarrier is given by

\[ y_{i,k}^{(m)}[l] = \sqrt{2} \int_{t_{i,k}}^{t_{i,k} + T_i} r(t) \cos(2\pi f_n t + \theta_{i,k}^{(m)}) c_{i,k}(t) dt. \]  

(4)

After the \( L_i \) decision statistics are obtained for each subcarrier for the desired user, the decision statistics are diversity combined through the maximal-ratio combining (MRC). Finally, bit decision is made on the data bits. The bit estimate of the \( l \)-th bit of the user \( k \) in the group \( i \) is given by

\[ \hat{d}_{i,k}[l] = \text{sgn} \left( \sum_{m=0}^{M-1} y_{i,k}^{(m)}[l] \alpha_{i,k}^{(m)} \right). \]  

(5)

2.2 MC-DS/CDMA System with MPG Scheme

The block diagram of the MC-DS/CDMA system with the MPG scheme is shown in Fig. 2. Fig. 2(a) shows the transmitter of the MC-DS/CDMA system with the MPG scheme. A group \( i \) user has a spreading code with a processing gain \( N_i = T_i / T_s \), where \( T_s = T_0 / L_i \), to transmit \( L_i \) bits during the bit duration of a group 0 user \( T_0 \). The spreading code of the user \( k \) in the group \( i \) is given by

\[ c_{i,k}(t) = \frac{1}{\sqrt{T_i}} \sum_{j=0}^{N_i-1} c_{i,k}[j] p_c(t - jT_s) \]  

(6)

where \( c_{i,k}[j] \in \{-1,1\} \), \( j = 0,1,\ldots,N_i-1 \), is the \( j \)-th element of a spreading code assigned to the user \( k \) in the group \( i \), and \( p_c(t) \) is a unit-amplitude rectangular pulse with duration \( T_s \). The baseband signal transmitted by the user \( k \) in the group \( i \) over the \( m \)-th subcarrier is given by

\[ s_{i,k}^{(m)}(t) = E_b / T_s M \sum_{j=-M/2}^{M/2-1} b_{i,k}[j + jL_i] c_{i,k}(t - jT_s) \]  

(2)

where \( E_b \) is the bit energy and \( b_{i,k}[j] \in \{-1,1\} \) is the \( j \)-th source bit of the user \( k \) in the group \( i \).

Assume that the channel suffers from the Rayleigh-distributed fading and has an additive white Gaussian noise (AWGN), \( n(t) \), with the power spectral density of \( N_0 / 2 \) W/Hz.

Fig. 1(b) shows the receiver of the MC-DS/CDMA system with the MPG scheme. The received signal at the receiver is given by

\[ r(t) = \sqrt{2} \sum_{m=0}^{M-1} \sum_{n=0}^{K-1} \alpha_{i,k}^{(m)}(t - \tau_{i,k}) \cos(2\pi f_n t + \theta_{i,k}^{(m)}) + n(t) \]  

where \( \tau_{i,k} \) is the time delay of the user \( k \) in the group \( i \), \( f_n \) is the center frequency of the \( m \)-th subcarrier, \( \alpha_{i,k}^{(m)} \) is the Rayleigh-distributed fade envelope and \( \theta_{i,k}^{(m)} \) is the phase uniformly distributed over \([0, 2\pi]\) for the \( m \)-th subcarrier of the user \( k \) in the group \( i \). The received signals over all subcarriers are down-converted and despread by the \( L_i \) spreading codes of the desired user. For the user \( k \) in the group \( i \), the decision statistic for the \( l \)-th bit over the \( m \)-th subcarrier is given by

\[ y_{i,k}^{(m)}[l] = \sqrt{2} \int_{t_{i,k}}^{t_{i,k} + T_i} r(t) \cos(2\pi f_n t + \theta_{i,k}^{(m)}) c_{i,k}(t) dt. \]  

(4)

After the \( L_i \) decision statistics are obtained for each subcarrier for the desired user, the decision statistics are diversity combined through the maximal-ratio combining (MRC). Finally, bit decision is made on the data bits. The bit estimate of the \( l \)-th bit of the user \( k \) in the group \( i \) is given by

\[ \hat{d}_{i,k}[l] = \text{sgn} \left( \sum_{m=0}^{M-1} y_{i,k}^{(m)}[l] \alpha_{i,k}^{(m)} \right). \]  

(5)
which is identical to (3). The received signals over all subcarriers are down-converted and despread by the desired user’s spreading code. For the user $k$ in the group $i$, the decision statistic for the $l$-th bit over the $m$-th subcarrier is given by

$$y_k^{(m)}[l] = \sqrt{2} \sum_{m=0}^{N-1} \sum_{k=0}^{K-1} \alpha_k^{(m)} \alpha_{k,l}^{(m)} (t-t_{k,l}) \cos(2\pi f_m t + \theta_{k,l}^{(m)}) \ .$$

(8)

After the decision statistic is obtained for each subcarrier for the desired user, the decision statistics are diversity combined through the maximal-ratio combining (MRC). Finally, bit decision is made on the data bits. The bit estimate of the $l$-th bit of the user $k$ in the group $i$ is given by

$$\hat{d}_{k,l}[l] = \text{sgn} \left( \sum_{m=0}^{N-1} y_k^{(m)}[l] \cdot \alpha_k^{(m)} \right) \ .$$

(9)

3. PERFORMANCE ANALYSIS

Assume that all subbands of a MC-DS/CDMA system are disjoint and subject to independent fading and the receiver has perfect synchronization. Assume that all users transmit with same signal-to-noise ratio (SNR) per bit using BPSK modulation.

3.1 MC-DS/CDMA System with Multicode Scheme

Consider a subcarrier in the MC-DS/CDMA system with processing gain $N$ and chip duration $T_c$. Assume that a user with data rate $R_i$ uses $R_i/R_0$ spreading codes in parallel to transmit its data and the orthogonal Gold codes are used as the spreading codes. For a group $i$ user, the SNR of the signal in each subcarrier is given by [3]

$$\gamma_i = \frac{\alpha^2}{2} \left[ \frac{M}{2E_b/N_0} + \frac{1}{3N} \left( \sum_{j=1}^{K_i} R_j - R_0 \right) \right] E[\alpha^2] \ .$$

(10)

where $E_b$ is the bit energy, $\alpha$ is the Rayleigh fading amplitude of the desired user, and $E[\alpha^2]$ is the expected signal strength. The SNR of the signal in each subcarrier $\gamma_i$ is exponentially distributed since $\alpha^2$ is exponentially distributed. The expectation of $\gamma_i$ is given by

$$\gamma_i = \frac{1}{2} \left[ \frac{M}{2E_b/N_0} + \frac{1}{3N} \left( \sum_{j=1}^{K_i} R_j - R_0 \right) \right] E[\alpha^2] \ .$$

(11)

The bit error rate of a group $i$ user over a subcarrier is given by [7]

$$P_{k;i} = \int_0^\infty P_e(y_i) \frac{1}{\gamma_i} e^{-y_i \gamma_i} dy_i = \frac{1}{2} \left( 1 - \frac{\gamma_i}{1 + \gamma_i} \right) \ .$$

(12)

where $P_k(y_i)$ is the bit error rate for the SNR of $\gamma_i$. From (13) the bit error rate of a group $i$ user after maximal-ratio-combining is given by

$$P_{k;i} = \left( \frac{1}{2} \left( 1 - \frac{\gamma_i}{1 + \gamma_i} \right) \right)^M \left( \sum_{m=0}^{N-1} \frac{M - 1 + m}{m} \right) \ .$$

(13)

3.2 MC-DS/CDMA System with MPG Scheme

Consider a subcarrier in the MC-DS/CDMA system with the MPG scheme. Assume that the orthogonal Gold codes are used as the spreading codes with constant chip duration $T_c$. For a group $i$ user, the SNR of the signal in each subcarrier is given by [3]

$$\gamma_i = \frac{\alpha^2}{2} \left[ \frac{M}{2E_b/N_0} + \frac{1}{3N} \left( \sum_{j=1}^{K_i} R_j - R_0 \right) \right] E[\alpha^2] \ .$$

(14)

where $E_b$ is the bit energy, $\alpha$ is the Rayleigh fading amplitude of the desired user, and $E[\alpha^2]$ is the expected signal strength. The SNR of the signal in each subcarrier $\gamma_i$ is exponentially distributed since $\alpha^2$ is exponentially distributed. The expectation of $\gamma_i$ is given by

$$\gamma_i = \frac{1}{2} \left[ \frac{M}{2E_b/N_0} + \frac{1}{3N} \left( \sum_{j=1}^{K_i} R_j - R_0 \right) \right] E[\alpha^2] \ .$$

(15)
where $E_b$ is the bit energy, $\alpha$ is the Rayleigh fading amplitude of the desired user, and $E(\alpha^2)$ is the expected signal strength. The SNR of the signal in each subcarrier $\gamma_i$ is exponentially distributed since $\alpha^2$ is exponentially distributed. The expectation of $\gamma_i$ is given by

$$\bar{\gamma}_i = \frac{1}{2} \left( \frac{M}{2 \cdot E_0} + \frac{1}{3N} \sum_{j=1}^{M} \frac{R_j}{R_i} K_j - 1 \right)^{-1}.$$  \hspace{1cm} (16)

The bit error rate of a group $i$ user over a subcarrier, $P_{b,i}$, is given by [7]

$$P_{b,i} = \frac{1}{2} e^{-\frac{\gamma_i}{2}} \cdot d\gamma_i = \frac{1}{2} \left( 1 - \frac{1}{1 + \gamma_i} \right)$$  \hspace{1cm} (17)

where $P_b(y_i)$ is the bit error rate for the SNR of $y_i$. From (17) the bit error rate of a group $i$ user after maximal-ratio-combining is given by

$$P_{e,i} = P_{b,i} \cdot \sum_{m=0}^{M-1} \left( 1 - P_{b,i} \right)^m$$

$$= \left[ \frac{1}{2} \left( 1 - \frac{1}{1 + \gamma_i} \right) \right] \cdot \sum_{m=0}^{M-1} \left( 1 - \frac{1}{1 + \gamma_i} \right)^m.$$  \hspace{1cm} (18)

4. Successive Interference Canceller (SIC)

To reduce the effect of MAI, SIC is applied to the multirate MC-DS/CDMA systems [6]. Assume that the receiver knows the data rates and spreading codes of the received signal and $K$ bits are received during $T_0$. The received signal is despread by the $K$ correlators and the largest is selected among $K$ correlator outputs. The corresponding user’s signal is respread using the correlator output and spreading code, and then subtracted from the received signal. Its result is despread by $K-1$ correlators other than one used in the first cancellation. The largest is selected among $K-1$ correlator outputs. The corresponding user’s signal is respread using the correlator output and spreading code, and then subtracted from the received signal. This process is repeated until the bit with the smallest correlator output is detected. After all bits of all users are detected in each subcarrier, the decision statistics of each user are maximal-ratio-combined, and finally bit decision is made.

5. Simulation Results

Consider two asynchronous multirate MC-DS/CDMA systems having three data rates: one with the multicode scheme and the other with the MPG scheme. Suppose that BPSK is used as modulation, the number of subcarriers $M$ equals 4, and the orthogonal Gold code is used as a spreading code for each user. Suppose that a high rate (HR) user transmits 4 bits and a medium rate (MR) user transmits 2 bits during the bit duration of a low rate (LR) user, $T_0$. Assume that the channel has frequency-selective fading with normalized Doppler frequency $f_d T_0 = 0.001$, where $T_0$ is the bit duration of a LR user. Also assume that the receiver knows the spreading codes of all users, and has perfect synchronization and channel estimation.

Fig. 3 shows the BER of the receiver of the multirate MC-DS/CDMA system in a Rayleigh fading channel having the 1 HR user, 2 MR users, and 4 LR users for $N = 32$, 64, and 128. In Fig. 3, it is shown that the HR user has smaller BER than the LR user due to the higher power of the HR user.
signal and the BER of the receiver becomes smaller as the processing gain becomes higher. It is also shown that the system with the multicode scheme has slightly better performance than the system with the MPG scheme when the processing gain is high. But the performance difference between two systems is not significant.

Fig. 4 shows the BER of the receiver of the multirate MC-DS/CDMA system with SIC in a Rayleigh fading channel having the 3 HR users, 3 MR users, and 3 LR users for $N=32$ and 64. Without SIC, it is shown that the system with the multicode scheme has almost same performance as the system with the MPG scheme and the HR user has better performance than the LR user due to the higher power of the HR user signal. It is shown that the systems achieve significant performance improvement by applying SIC to their receivers. Moreover, when SIC is applied, it is shown that the system with the multicode scheme has better performance than the system with the MPG scheme. It is because the HR and MR users in the former system have higher processing gain than those in the latter system.

6. CONCLUSIONS

In this paper, two multirate schemes are considered for the MC-DS/CDMA system in the frequency-selective channel. The BERs of the systems are obtained by analysis and simulation in a Rayleigh fading channel with perfect channel estimation. It is shown that the system with the multicode scheme has slightly better performance than the system with the MPG scheme. Each of the two systems achieves significant performance improvement by applying SIC to its receivers. Also it is shown that the system with the multicode scheme has better performance than the system with the MPG scheme when SIC is applied.

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REFERENCES