Performance of a Multicarrier DS/CDMA System with Adaptive Antenna Array in a Nakagami Fading Channel

Jin Young Kim* and Jae Hong Lee**

* Department of Electrical Engineering, Princeton University
Princeton, New Jersey 08544, U.S.A.
** School of Electrical Engineering, Seoul National University
Shinlim-dong, Gwanak-gu, Seoul 151-742, Korea

Abstract—In this paper, a multicarrier DS/CDMA system with adaptive antenna array is proposed for a multipath fading channel. A multipath fading channel is modeled as a Nakagami-m fading channel. The performance is evaluated in terms of bit error probability, and system capacity for the multicarrier DS/CDMA system with adaptive antenna array is estimated. From the analytic and simulation results, it is shown that the overall system capacity increases significantly compared to the system without adaptive antenna array.

I. INTRODUCTION

For a future wireless communication system, high-speed and high-quality services supporting voice, data, and video require high transmission rates up to several Mbps [1]. However, a multipath fading channel has multiple propagation paths which impose limitation on its maximum transmission rate. To mitigate this limitation on transmission rate, a multicarrier transmission technique has been proposed [2-6]. In a multicarrier transmission technique, an input data sequence is multiplexed and modulated onto a number of subcarriers in parallel. The transmission rate of each subcarrier is selected such that the bandwidth of each subcarrier is much less than the coherence bandwidth of a channel to ensure negligible intersymbol interference. Since the input data sequences are transmitted in parallel, duration of a data sequence for a subcarrier is much larger than that of input data sequence.

One of the approaches to improve a DS/CDMA (direct-sequence/code-division-multiple-access) system performance is the use of spatial filtering at a base station with adaptive antenna array [7-10]. The adaptive antenna array is also termed as smart antenna or software antenna leading to the concept of intelligent antenna. The adaptive antenna array has been considered for the third-generation mobile communication system including a multicarrier DS/CDMA system and a packet radio network [11,12]. The adaptive antenna array has potential to provide designers with an extra dimension of SDMA (space-division-multiple-access) along with FDMA, TDMA, and CDMA in solving the problems related with the realization of the mobile communication system. It is widely accepted that an adaptive antenna array will offer potential solutions to a number of the key requirements since it provides many promising features such as high capacity, high spectrum efficiency, and more degrees of freedom to adjust cell coverage characteristics, leading to more efficient use of radio resources.

The extensive researches on adaptive antenna array are currently performed worldwide for applications to various kinds of target systems. In Korea, ETRI (Electronics and Telecommunications Research Institute) is developing the adaptive antenna testbed called CTS (CDMA adaptive antenna array testbed system) using PAT (performance analysis tool). This adaptive antenna system is mainly focused on DS/CDMA applications. In Japan, NTT takes the initiative on the development of adaptive antenna array and is aiming at both TDMA and CDMA applications. In U.S.A., AT&T Bell Lab. and Stanford University are developing adaptive antenna testbed and have done the field trials for both TDMA and CDMA systems while in Europe, EC (European community) is performing TSUNAMI project for applications to TDMA and CDMA systems.

The promising techniques such as multicarrier transmission and adaptive antenna array can be combined to achieve more improved performance compared with the conventional system. When these two techniques are combined, a full use of advantages of both techniques can be made.

In this paper, the performance of a multicarrier DS/CDMA system with adaptive antenna array is proposed and simulated in a Nakagami fading channel. The performance is evaluated in terms of bit error probability. The multipath fading channel is modeled as a Nakagami-m distribution which has flexibility to model the fading channel. A linear antenna array with equi-spacing identical array elements and half wavelength antenna spacing is considered.

This paper is organized as follows: In Section II, the system model of a multicarrier DS/CDMA system and channel model are described. In Section III, the performance of a proposed multicarrier DS/CDMA system is analyzed in a Nakagami fading channel. In Section IV, the simulation examples are shown. Finally, the conclusions are drawn in Section V.
II. SYSTEM MODEL

A. System Description

In Fig. 1 (a) to (c), the block diagrams of a transmitter and a receiver are shown. The input data stream is first serial-to-parallel converted to a number of lower data rate streams. Each stream feeds a number of parallel streams with the same rate. On each of the latter streams, bits are interleaved and spread by a PN code with a suitable chip rate. Then, these streams modulate orthogonal carriers with a successively overlapping bandwidth.

In Fig. 1. (a), input data sequence with bit duration $T_l$ is serial-to-parallel converted into $M$ parallel streams, each of which has duration of $T_i = MT_l$. On each branch of the $S$ branches, the data streams are interleaved such that on two contiguous branches, the replicas of the same data bit are separated by some interval. The interleaver is useful to randomize burst errors or to spread out adjacent symbols over time intervals greater than the noise burst duration. Each stream feeds $S$ parallel branches, each of which has a same data stream. In each of $S$ parallel branches, data sequence is multiplied by a spreading sequence and is modulated by carrier. The output signals of $MS$ branches are summed to be transmitted.

At the receiving side of the $k$th user as shown in Fig. 4.1. (b), the transmitted signal is first processed at the adaptive antenna array. At the adaptive antenna array, the received signal passes through an antenna array and the output of the antenna array is processed at the spatial filter which is controlled by an adaptive processor. The signals from the receiving antennas is combined to mitigate the MAI using adaptive antenna array. The tap weights are adaptively updated to form a beam with the maximum gain to the desired user and a beam with nulls to the interfering users. The receiver of the $k$th user employs $MS$ matched-filter (MF) detectors, each tuned and synchronized to one of the carriers. The output of the adaptive antenna array is despread by the PN code and the despread output passes through from the first carrier processor to the $M$th carrier processor. The data decision is made using the output of the each carrier processor, and the results of data decision are parallel-to-serial converted. Finally, the estimated data stream over the transmitted data stream is obtained.

At the $i$th carrier processor as shown in Fig. 4.1. (c), the despread signal is multiplied by each carrier and integrated over the duration of $T_l$. The output of integrator is deinterleaved and the output of each branch of $S$ branches are summed.

B. Adaptive Algorithm

The selection of adaptive algorithm for adaptive weights is very important in that it determines both convergence rate and hardware complexity required to implement the algorithm. The tap updating algorithms originate from the adaptive filter theory.

There have been many adaptive algorithms for tap weight updating in the time and spatial domain. In the time domain processing, Applebaum algorithm, LMS (least mean square), RLS (recursive least square), CMA (constant modulus algorithm), and DMI (direct matrix inversion), etc. have been proposed. The Applebaum algorithm is applicable only when DOA (direction of arrival) of the desired signal is known beforehand. The LMS algorithm has been widely used for tap coefficient adaptations of an adaptive processor in an antenna array, but it causes signal acquisition and tracking problems due to its slow convergence in a multipath fading channel. The CMA is useful when the constant envelope of modulated signal is maintained. DMI algorithm has been proposed due to its fast convergence property, however, it is computationally too complex and may cause numerical instability. The RLS algorithm is known to achieve faster convergence than LMS algorithm and is less computationally complex than DMI algorithm [13]. Thus, of many adaptive algorithms, RLS algorithm is employed in this paper. In the spatial domain processing, DFT (discrete Fourier transform), MEM (max-
imum entropy method), MUSIC (multiple signal classification), and ESPRIT (estimation of signal parameters via rotational invariance technique), etc. They are focused on DOA estimation by spectral analysis in the space domain.

C. Channel Model

Most of studies so far have assumed that fluctuation of the received signal envelope follows Rayleigh distribution in a macrocell environment. However, when a specular component is involved, it seems reasonable to assume that received signal envelope follows the Nakagami m-distribution proposed by Nakagami [14]. This is because the Nakagami m-distribution can describe not only Rayleigh fading but also Rician fading by adjusting the value of fading index m.

The p.d.f. of a Nakagami fading channel for the kth user is given by

\[ f_{\text{Nak}}(\beta, \Omega) = \frac{2}{\Gamma(m)} (\frac{\beta}{\Omega})^{2m-1} \exp(-\frac{\beta}{\Omega}) ]^{-m}, \]

where \( \beta, \Omega > 0, m \geq 0.5, \Gamma(m) = \int_{0}^{\infty} t^{m-1} e^{-t} dt \) for \( m > 0 \) is Gamma function, \( E[\beta^2] = \Omega, \) and m is a fading index of Nakagami fading channel representing the severity of fading. The fading index m is assumed to be the same for all users and all paths.

From the tapped-delay-line (TDL) model for the multipath fading channel, the lowpass equivalent impulse response of channel model is given by

\[ h_k(t) = \sum_{i=1}^{L_k} \beta_{k,i} \delta(t - \tau_{k,i}), \]

where \( L_k \) is the number of multipath for the kth user, \( \beta_{k,i} \) is Nakagami-m distributed path strength, \( \tau_{k,i} \) is tap spacing of the TDL fading model, and \( \alpha_{k,i} \) is the phase uniformly distributed [0, 2\pi].

A multipath fading channel is characterized by its multipath intensity profile (MIP) which is the average power at the output of the channel as a function of path delay. Actual measurements in an urban environment indicate that the MIP is exponential. Let the maximum delay spread of the multipath fading channel be \( T_d \). Then the number of resolvable multipaths \( L \) is given by

\[ L = \lceil \frac{T_d}{T_e} \rceil + 1. \]

III. PERFORMANCE ANALYSIS

In the performance analysis, the followings are assumed: 1) K users in a single sector are uniformly distributed, 2) hexagonal cell pattern is considered, 3) perfect power control is achieved by adaptive power control algorithm, and 4) perfect chip synchronization is achieved.

A. Interference Modeling

For a single sector with K users, the transmitted signal of the kth user is given by

\[ s_k(t) = \sum_{i=1}^{M} \sqrt{2P_k \beta_{k,i}} c_k(t) \cos(\omega_k t + \phi_{k,i}), \]

where \( P_k \) is the transmitted power per carrier, \( \beta_{k,i} \) is data bit sequence of the jth carrier \( (j = 1, \cdots, M) \), \( c_k(t) \) is spreading sequence, \( \omega_k \) is the kth carrier frequency, and \( \phi_{k,i} \) is a random phase for each carrier. The data sequence is multiplied by a spreading sequence and modulated on a carrier. The data bit sequence and spreading sequence are assumed to have a periodic train which takes a value of 1, -1. The bit and chip waveforms are assumed to be rectangular pulses.

The received signal is given by

\[ r(t) = \sum_{k=1}^{K} \sum_{i=1}^{M} \sum_{l=1}^{L} \sqrt{2P_k \beta_{k,i}} b_{k,i}(t - \tau_{k,i} - \tau_l) c_k(t - \tau_{k,i}) \cos(\omega_k t + \psi_{k,i,l}) B(\theta_{k,i,l}) + n(t), \]

where \( \psi_{k,i,l} = (\phi_{k,i,l} + \alpha_{k,i,l} - \omega_{k} \tau_{k,i} - \omega_{k} \tau_l) \) is a random carrier phase, \( \tau_k \) is a propagation delay of the kth user, \( B(\theta_{k,i,l}) \) is beam pattern of beamformer, and \( n(t) \) is AWGN with zero mean and power spectral density \( N_0/2 \). The \{\tau_k\} and \{\psi_{k,i,l}\} are i.i.d. uniformly distributed random variables in \([0, T_1)\) and \([0, 2\pi)\), respectively. Without loss of generality, it is assumed that user 1 is reference user and \( \tau_1 = 0 \). The MF output of the lth path of the carrier j of reference user is given by

\[ Z_{1,1} = \int_{t_{1,1}}^{t_{1,1} + \tau_1} r(t) c_1(t - \tau_{1,1}) \cos(\omega_1 t + \psi_{1,1,l}) dt. \]

When RAKE receiver is employed for every branch of MS branches, each RAKE receiver consists of \( \lambda \) MF’s which lock to the first \( \lambda \) paths (\( 1 \leq \lambda \leq L \)). For a bit transmitted on carrier group j (\( j = 1, \cdots, M \)), the decision statistics of the \( S \lambda \) MF’s are summed. The decision statistic is given by

\[ Z_{1,j} = \sum_{v=1}^{S} \sum_{i=1}^{\lambda} Z_{1,v} = D_x + I_1 + I_2 + I_3 + I_4 + \eta, \]

where \( \eta \) is the relative carrier number in the jth carrier group, \( p \) is the absolute carrier number. In (7), \( D_x \) is the desired signal term for \( k = 1 \) and \( p = i \), and given by

\[ D_x = \sqrt{\frac{P}{2}} T_1 b_0 \sum_{v=1}^{S} \sum_{i=1}^{\lambda} \beta_{1,v,i} B(\theta_{1,v,i}). \]

From (7), four terms of interferences and the background noise are as follows [15,16]: 1) \( f_1 \) : interference from the \( L - 1 \) paths other than \( i \) of the carrier p of reference user,
2) $I_2$: interference from the $L-1$ paths other than $i$ of the carriers other than the carrier $p$ of reference user, 3) $I_3$: interference from the $L$ paths of the carrier $p$ of the interfering users, 4) $I_4$: interference from the $L$ paths of the carriers other than the carrier $p$ of the interfering users, and 5) $\eta$: noise component.

B. Bit Error Probability

Gaussian approximation is used in calculating multi-user and multipath interferences. We assume that the transmitted data is 'one'. From the above analysis, the mean and the variance of $Z_{1,j}$ are given by

$$E[Z_{1,j}] = \sum_{v=1}^{S} \sum_{i=1}^{\lambda} \sqrt{P_{T}^{2} \beta_{1,p,i} + B(\theta_{1,p,i})}, \quad (9)$$

$$\text{var}[Z_{1,j}] = \text{var}[I_1] + \text{var}[I_2] + \text{var}[I_3] + \text{var}[I_4] + \text{var}[\eta]. \quad (10)$$

Conditional bit error probability conditioned on $X$ and $j$ is given by

$$Pr[e|j,X] = \frac{1}{2} \text{erfc}(X\sqrt{Y}), \quad (11)$$

where $X = \sum_{v=1}^{S} \sum_{i=1}^{\lambda} \beta_{1,p,i} + B(\theta_{1,p,i}) [16], Y = [\sum_{v=1}^{S} \sum_{i=1}^{\lambda} \beta_{1,p,i} + B(\theta_{1,p,i})] [16], G$ is processing gain, and $\text{erfc}(z) = 2Q(\sqrt{2z})$ is complementary error function calculated from Gaussian tail integral $Q(z) = \int_{\infty}^{10} \frac{1}{\sqrt{2\pi}} \exp(-t^2)dt$. Then, bit error probability is obtained by

$$Pr[e] = \frac{1}{M} \sum_{j=1}^{M} \int_{-\infty}^{\infty} \frac{1}{2} \text{erfc}(X\sqrt{Y})f(X)dX, \quad (12)$$

where $f(X)$ is a p.d.f. of $X$.

C. Capacity Estimate

A capacity of a DS/CDMA system is defined as the maximum number of users which the system can accommodate. Generally, the following factors affect the DS/CDMA system capacity: 1) processing gain, 2) $E_b/N_0$, 3) voice activity factor, 4) sectorization gain, 5) propagation conditions such as fading and shadowing, and 6) blocking probability for voice calls. The capacity is typically estimated with three constraints: 1) outage probability, 2) bit error probability, and 3) PN acquisition performance [17]. Unlike the capacity of FDMA or TDMA systems, the capacity of a CDMA system is soft in that there is not a fixed number of channels or time slots available for use in each cell. The previous approaches for capacity estimate of a CDMA system have concentrated on a single-carrier DS/CDMA system in a fading environment with or without shadowing. However, the capacity estimate for a multicarrier DS/CDMA system has rarely been made so far. The capacity is defined as

$$C = K_{\max}, \text{ for } P_{\text{out}} < P_{\text{out},c;f}. \quad (13)$$

where $P_{\text{out}}$ is outage probability and $P_{\text{out},c;f}$ is reference outage probability. The sectorization gain is not considered in the capacity estimate because we are interested only in a sector. Since the reverse link is the limiting link in terms of user capacity and the adaptive antenna array is installed in a base station, we focus our attentions to the reverse-link capacity [18].

IV. SIMULATION RESULTS

The proposed multicarrier DS/CDMA system with adaptive antenna array is simulated for the MPSK modulation for data and chip sequences in the reverse link. For the simulation examples, vehicle speed $v = 12$ km/hour, carrier frequency $f_c = 1.8$ GHz, Doppler frequency $f_d = v/c = 20$ Hz, data rate $R_d = 3.84$ kbps, chip rate $R_c = 4.9152$ Mcps, processing gain $G = R_c/R_s = 128$, the number of multipaths $L_r = 2$, exponential MIP, and the forgetting factor of RLS algorithm $\delta = 0.05$ were assumed. The uniform linear array with half wavelength antenna spacing is considered.

In Fig. 2, bit error probability vs. SNR is shown for $M = 6, S = 4, N_s = 8, K = 10$, Gold sequence, and the various values of $\sigma$. It is shown that larger $\sigma$ produces better BER performance because the $m$ larger than 1 represents milder fading condition resulting in a Rician fading channel.

In Fig. 3, bit error probability vs. SNR is shown for $m = 1, M = 6, S = 4, K = 10$, a Gold sequence, and the various numbers of array elements $N_s$. It is shown that BER performance is significantly improved as the number of array elements increases.

In Fig. 4, the capacity vs. fading index is shown for $\sigma = 8$ dB, voice activity factor $= 0.8$, $P_{\text{out}} = 10^{-2}, M = 6, S = 4, N_s = 8$, Gold sequence. It is shown that the system capacity is increased by about twice by 8 adaptive array elements. The degree of capacity enhancement can be varied according to the given system parameters and propagation conditions.

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The performance of the proposed multicarrier DS/CDMA system with adaptive antenna array was analyzed and simulated in a Nakagami fading channel. The performance was evaluated in terms of bit error probability in a single sector of a cell. In the performance analysis, the synchronization at chip and bit levels is assumed to be perfect in the time and frequency domains. However, the perfect synchronization is not always maintained in the multipath fading channel. Therefore, the effect of imperfect synchronization on performance should be evaluated as a companion work of this paper.

We confirmed that higher data rate and better BER performance can be induced by the reduction of multipath effects through spatial processing since the data rate and BER performance are limited by multipath fading. From the simulation results, it was shown that the BER performance of the proposed multicarrier DS/CDMA system is improved by using adaptive antenna array, leading to the increase of system capacity. From the implementation point-of-view, the adaptive antenna array consists of a phase array, downconverter, A/D converter, and an adaptive signal processor (or a field programmable array). The adaptive antenna array can be applied to the performance improvement of IS-95 based CDMA system and the design of the next-generation mobile communication systems such as IMT-2000.

REFERENCES


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