다중 입출력과 적응형 빔형성 기술 결합기법을 적용한 직교주파수분할 다중 접속시스템의 성능 분석

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Performance Analysis of MIMO-OFDMA System Combined with Adaptive Beamforming

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요 약

본 논문에서는 공간 다중화 방식과 적응형 빔 형성 기법을 결합한 다중 안테나 시스템에 대한 하향 링크 성능이 다루어진다. 이 결합 기법은 IEEE 802.16e 표준에 기반한 한국형 직교 주파수 분할 다중 접속 표준인 와이브로 시스템에 적용되었다. 성능 분석은 고정 소수점 모의실험 테스트 장비 및 컴퓨터 모의실험을 사용하여 수행되었다. 실험결과는 와이브로 시스템에 다중 입출력과 적응형 빔형성 기법이 결합되어 적용될 경우 기존의 단순한 다중 입출력 방식만 사용할 때보다 프레임 에러율 1%를 기준으로 QPSK에 대해서는 3dB, 16QAM에 대해서는 2.5dB의 신호 대 잡음비 이득을 제공함이 밝혀졌다. 고정 소수점 모의실험 테스트 장비 구현과 이를 이용한 실험을 통해, 다중 입출력과 적응형 빔형성의 결합 기법이 와이브로 기지국에 적용 가능함을 보여주었다.

Key Words : MIMO, Adaptibve Beamforming, OFDMA, 802.16e

ABSTRACT

This paper details the downlink performance analysis of an multiple antennas system that combines adaptive beamforming and spatial multiplexing (SM) Multiple Input Multiple Output (MIMO). The combination of MIMO signal processing with adaptive beamforming is applied to WiBro, the South Korean Orthogonal Frequency Division Multiple Access (OFDMA) system that follows the IEEE 802.16e standard. Performance analysis is based on the results of experiments and simulations obtained from a fixed-point simulation testbed. Simulations demonstrate that the MIMO Beamforming OFDMA system improves the required signal to noise ratio (SNR) over the conventional MIMO OFDMA system by 3 dB (QPSK) / 2.5 dB (16-QAM) for the frame error rate (FER) of 1% in the WiBro signal environments. From the implementation of the fixed-point simulation testbed and its experimental results, we verify the feasibility of the MIMO Beamforming technology for realizing a practical WiBro base station.

Ⅰ. Introduction

A potential application of MIMO principle is the next-generation wireless metropolitan area network (WMAN). The current WMAN standard IEEE 802.16e[1] is based on orthogonal frequency division multiple access (OFDMA). The high data rate extension of this standard could be based on MIMO[2].

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This leads to a promising combination of the data rate enhancement of MIMO with the relatively high spectral efficiency. However, one challenge of wireless MAN systems is that they are mainly deployed in outdoor environments. These environments are typically characterized by correlated fading channels causing a performance loss of a conventional MIMO system[3,4].

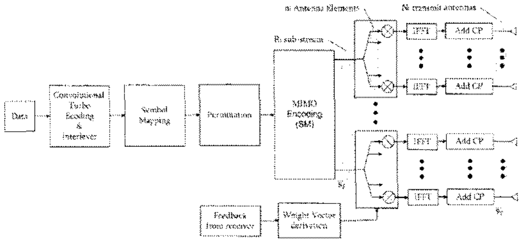
For these reasons, Korea Telecom (KT) has launched a project which aims to develop a WMAN system employing an advanced MIMO that combines spatial multiplexing with the adaptive beamforming which gives good bit error rate (BER) performance[5,6] especially in the correlated fading channel environment (hereinafter referred to as "A-MIMO").

The primary contribution of this paper is to realize the concept of A-MIMO while focusing on the IEEE 802.16e standard. Although previous studies have addressed the combination of MIMO with a beamforming[7-10], a good overview and clarification of experimental results of an A-MIMO system based on the WiBro/IEEE 802.16e standard has not yet been discussed in the literature. In order to verify the applicability of the A-MIMO technology to a practical WiBro base station, we have implemented a fixed-point simulation testbed using digital signal processor (DSP) boards.

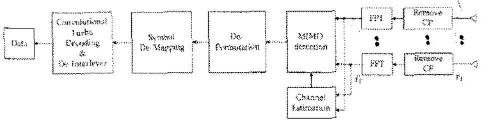
This paper is organized as follows. Section Ⅱ contains the A-MIMO OFDMA system supporting the WiBro physical (PHY) layer specification. Section Ⅲ describes the development of signal model for the A-MIMO OFDMA system. In Section Ⅳ, we present the design of fixed-point simulation testbed. In Section Ⅴ, we provide a performance analysis in terms of frame error rate (FER) obtained from the implemented testbed. The conclusions from this research are outlined in Section Ⅵ.

Ⅱ. System Description

Since the A-MIMO technology is particularly useful for downlink communication, we focus primarily on the downlink communication with N_t transmit and N_r receive antennas. Figure 1 illustrates a block diagram of the A-MIMO OFDMA system. Incoming bits from the A-MIMO OFDMA transmitter, which consists of multiple OFDMA transmitters, are symbol-processed according to a physical (PHY) layer specification of the IEEE 802.16e WMAN standard. The vector $\overline{S_F} = [S_1 \cdots S_{R_s}]$, where R_s indicates the number of symbols to be transmitted simultaneously at the transmitter, is assumed to be a MIMO encoded symbol vector in frequency domain. For the adaptive beamforming procedure, we define the number of transmit antennas comprising one antenna group as n_i; thus, $\mathbf{W}_i \in C^{n_i \times 1}$ is the weight vector for a single transmit symbol, S_i, $i = 1, \cdots, R_s$ where adaptive beamforming weight is determined by selecting eigenvector corresponding to the maximum eigenvalue of the received covariance matrices. It is noteworthy that adaptive beamforming operation is capable of obtaining a significant coherent beamforming gain since the TDD (Time Division Duplexing) method of IEEE802.16e provides excellent reciprocity between the downlink and uplink channels. N_c-point IDFT (Inverse Discrete Fourier Transformation) is carried out and a cyclic prefix (CP) is added over each branch prior to the final transmitting signal and transmitted through the antenna. At the receiver, the CP is removed; subsequently, the N_c-point Discrete



(a) Transmitter



(b) Receiver

Fig. 1. A-MIMO OFDMA System

Fourier Transformation (DFT) is performed for each receiver branch. Then, MIMO detection is done for each OFDM subcarrier for R_s parallel streams. De-permutation, de-modulation, de-interleaving, and convolutional turbo decoding is followed.

Ⅲ. A-MIMO OFDM Signal Model

In this section, given the system description of Section II, we develop a signal model of the ABF-MIMO OFDMA system. We focus on the development of the combined MIMO-OFDM signal model with ABF since IEEE 802.16e OFDMA standard is based on OFDM technology as a transmission scheme and our research explores the physical layer (i.e. OFDM) performance of the OFDMA system. ABF-MIMO OFDM signal model will be described after the overview of ordinary MIMO-OFDM signal model is presented. When there are n_i antennas are equipped in each beamforming antenna group (i.e. $N_t = N_G n_i$) and N_r antennas at the mobile station, the entire MIMO channel matrix can be derived as

$$H = \begin{bmatrix} h_1^1 & h_1^2 & \cdots & h_1^{N_G} \\ h_2^1 & h_2^2 & \cdots & h_2^{N_G} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R}^1 & h_{N_R}^2 & \cdots & h_{N_R}^{N_G} \end{bmatrix} \tag{1}$$

where h_i^j indicates the channel fading vector from the j-th antenna group at the base station to the i-th antenna at the mobile station. For a beamforming antenna group with n_i antenna element, h_i^j is a $1 \times n_i$ row vector as follow.

$$h_i^j = [h_{i,1}^j \ h_{i,2}^j \ \cdots \ h_{i,n_i}^j] \tag{2}$$

where $h_{i,m}^j$ is the channel fading between the mth antenna element in the j-th antenna group at the base station and the i-th antenna at the mobile station. As the system configuration of the proposed scheme shows, the transmit signal s is divided into N_s parallel signals $\overline{s_F} = [s_1 \cdots s_{N_S}]$ through the splitter. In this paper, we assume that the number of split symbols is equal to the number of beamforming antenna groups, i.e. $N_G = N_s$. Thus, the split transmit symbols are sent to different antenna groups to perform beamforming as below.

$$\tilde{s}_j = w_j s_j \tag{3}$$

where w_j is the beamforming weight vector for the j-th antenna group which is based on the Lagrange algorithm[11,12]. s_j after beamforming is converted into a $n_i \times 1$ column vector $\tilde{s}_j$. Assuming the channel is flat fading in each OFDM subcarrier, the received signal at the i-th antenna of the mobile station is expressed as

$$y_i = h_i^1 \tilde{s}_1 + \cdots + h_i^{N_G} \tilde{s}_{N_T} + \eta_i \tag{4}$$

where η_i is a spatially uncorrelated complex Gaussian noise vector. Then, the received signal for k-th subcarrier can be expressed as

$$y_i(k) = h_i^1(k) w_1(k) s_1(k) + \cdots + h_i^{N_G}(k) w_{N_G} s_{N_G}(k) + \eta_i(k) \tag{5}$$

We can construct the procedure into the matrix form as follows.

$$\begin{aligned} \begin{bmatrix} y_1(k) \\ y_2(k) \\ \vdots \\ y_{N_R}(k) \end{bmatrix} &= \begin{bmatrix} h_1^1(k)w_1(k) & h_1^2(k)w_2(k) & \cdots & h_1^{N_S}(k)w_{N_S}(k) \\ h_2^1(k)w_1(k) & h_2^2(k)w_2(k) & \cdots & h_2^{N_S}(k)w_{N_S}(k) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R}^1(k)w_1(k) & h_{N_R}^2(k)w_2(k) & \cdots & h_{N_R}^{N_S}(k)w_{N_S}(k) \end{bmatrix} \begin{bmatrix} s_1(k) \\ s_2(k) \\ \vdots \\ s_{N_S}(k) \end{bmatrix} + \begin{bmatrix} \eta_1(k) \\ \eta_2(k) \\ \vdots \\ \eta_{N_R}(k) \end{bmatrix} \\ &= \begin{bmatrix} h_1^1(k)w_1(k) & h_1^2(k)w_2(k) & \cdots & h_1^{N_G}(k)w_{N_G}(k) \\ h_2^1(k)w_1(k) & h_2^2(k)w_2(k) & \cdots & h_2^{N_G}(k)w_{N_G}(k) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R}^1(k)w_1(k) & h_{N_R}^2(k)w_2(k) & \cdots & h_{N_R}^{N_G}(k)w_{N_G}(k) \end{bmatrix} \begin{bmatrix} s_1(k) \\ s_2(k) \\ \vdots \\ s_{N_G}(k) \end{bmatrix} + \begin{bmatrix} \eta_1(k) \\ \eta_2(k) \\ \vdots \\ \eta_{N_R}(k) \end{bmatrix} \end{aligned} \tag{6}$$

$$y(k) = H(k)w(k)s(k) + \eta(k) = \tilde{H}(k)s(k) + \eta(k) \tag{7}$$

Ⅳ. Fixed-Point Simulation Testbed

In this section, we introduce an implementation of all-digital fixed-point simulation testbed for MIMO OFDMA system. Figure 2 illustrates a functional

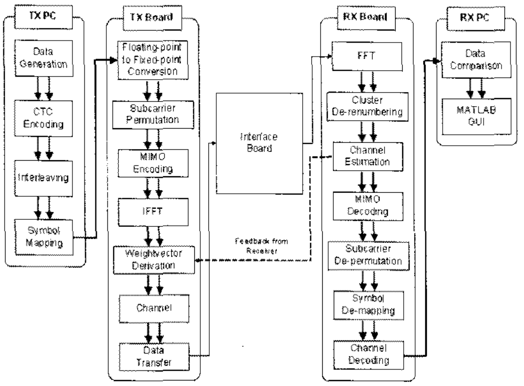


Fig. 2. Functional block diagram of Fixed-Point Simulation Testbed

block diagram of the simulation environment. At the transmit (TX) PC and TX DSP-based board, MIMO OFDMA data frames with/without adaptive beamforming are generated based on IEEE 802.16e WMAN standard for transmission. Main system design parameters are summarized in Table 1.

Table 1. Simulator Design Parameters

System Parameter	Value
Bandwidth	8.75MHz
FFT Size, N_c	1024
OFDM Symbol Duration	115.2usec
Guard Interval	12.8usec
TDD Frame Period	5msec
Number of Beamforming Antenna Groups, N_G	2 (A-MIMO)
Number of Antennas per Beamforming Antenna Group, n_i	4 (MMO Beamforming)
Number of total TX antennas, $N_T = N_G \times n_i$	2 (MIMO) 8 (A-MIMO)
Number of total RX antennas, N_r	2
Number of Data streams, N_s	2
Angle Spread	Zero Degree
Modulation	QPSK, 16-QAM
Forward Error Correction	CTC, R=1/2
MIMO Detection	Linear Equalization based on Zero-forcing criterion[16]
Channel Estimation	Linear Interpolation
Channel Model	Rayleigh Fading on Each Path based-on ITU-R Vehicular-A (60km/hr)[13]
Doppler Frequency	128 Hz
Time & Freq. Synchronization	Perfect

Given in Figure 2 and Table1, we describe the all-digital baseband signal processing flow as follows. Using MATLAB, the TX PC shown in Figure 2 performs abit-level processing which includes a randomized bit stream generation, convolutional turbo encoding, interleaving, and modulation, i.e., symbol mapping to QPSK or 16-QAM. Mapped symbols are then transferred to the DSP-based board in TX board through a RTDX-JTAG (Joint Test Action Group) interface. The board is composed of Texas Instruments (TI) TMS320C6416T DSP chip, 16 Mbytes SDRAM, 512 Kbyte Flash Memory, and external interface JTAG. The first processing in the DSP-based board is the conversion of floating-point symbols into corresponding 12-bits fixed-point symbols using a floating-to-fixed point converter, since baseband signal processing in DSP-based hardware requires fixed-point operation. Next, permutation are performed for the QPSK or 16-QAM symbols in 12-bits fixed-point format followed by MIMO encoding, i.e., spatial multiplexing. Thus, multiple data streams are created by a MIMO encoding function. Weight vectors for the adaptive beamforming are multiplied by MIMO-encoded symbol stream. For computing the weight vector, the Lagrange algorithm has been employed using uplink pilot signals for the downlink adaptive beamforming. IDFT is carried out for MIMO-encoded data stream multiplied with weight vector and then CP is appended. Thus, the generation of A-MIMO OFDMA data frame at the transmitter is completed in 12-bits fixed-point format. The last processing at the TX board is to convolve the created A-MIMO OFDMA data frame with 6-paths channel impulse responses of the ITU-R Vehicular-A channel model[13]. Dual port RAM-equipped interface board transfers the A-MIMO OFDMA data frames convolved with channel impulse responses to the receive (RX) DSP-based board through the RTDX JTAG interface. At the RX board, CP removal, DFT, and channel estimation is performed for each receiver path. Using the estimated channel coefficients, a linear equalization is carried out based on zero-forcing (ZF) criterion. Detected symbols are then de-permutated and de-mapped with the soft-decision, thus softly-demapped symbol values, i.e., log-likelihood ratio (LLR) values, are converted into the bit streams. De-interleaving and convolutional turbo decoding operation is followed consecutively for the incoming bit streams. Decoded bit streams are relayed to the RX PC and FER is calculated. In Figure 3, the implemented simulation testbed consisting of DSP-based TX/RX boards, PCs, and other necessary parts is shown.

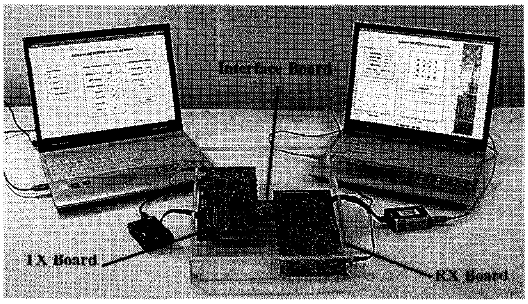


Fig. 3. Implemented Fixed-Point Simulation Testbed

V. Performance Analysis

In this section, we provide the calculation of practical SNR gain which can be obtained by combining beamforming with MIMO OFDM system. When adaptive beamforming technique is combined with a simple MIMO OFDM system, beamforming gain is expected to be obtained. However, it is noteworthy that there is some amount of loss in the beamforming gain due to following reason. From the literature[14], maximum achievable beamforming gain by array antenna structure can be derived as below assuming power-fair condition.

$$10\times\log(1+N_{BF}-1)\rho)\,\mathrm{dB} \tag{8}$$

where ρ represents spatial correlation coefficient between antennas and N_{BF} denotes the number of transmit antennas in a beamforming group. In other words, beamforming gain by antenna structure depends on both the number of transmit antennas and the amount ofspatial fading correlation between antennas. There is another important factor affecting the performance of beamforming gain the usage of OFDM transmission. A previous research[15] has shown that OFDM system transforms a highly spatially correlated channel impulse response to a less spatially correlated channel frequency response inherently in the presence of rich multipath channel environment. Thus, multiple antenna OFDM system (A-MIMO OFDM system in this paper) experiences a reduction of spatial correlation between antennas in a multi-paths channel environment. Correspondingly, practical beamforming gain in multiple antenna OFDM system becomes less than theoretically maximum gain under a multi-paths channel condition.

Figure 4 illustrates the FER performances obtained from experiments and simulations of 8×2 A-MIMO system and 2×2 MIMO system for the QPSK modulation. For the 1% of FER, the experimental data prove that 8×2 system obtained approximately a 3 dB gain in SNR compared to 2×2 system. The contribution of a 3 dB gain in SNR arises solely from the array gain of which the theoretical value can be, at most, 6dB (10×log(4) =6dB). In the mean time, as described in previous part of this section, the loss of 3 dB in the SNR gain is explained mainly due to spatial correlation and OFDM characteristics. Figure 5 shows the FER performances of both systems for 16-QAM, as a function of the SNR per subcarrier of each antenna element. At the FER of 1%, the data show that 8×2 system

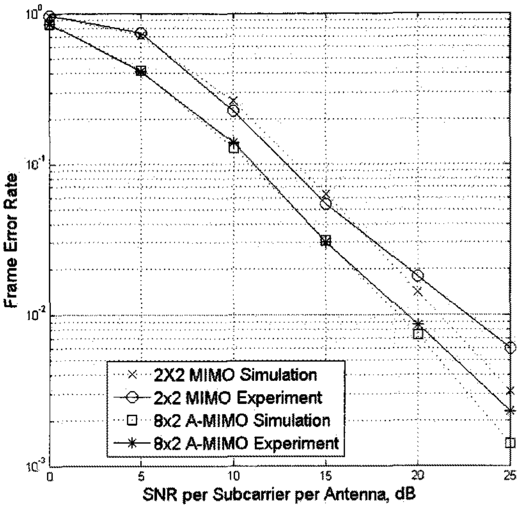


Fig. 4. FER performance comparison between 8×2 and 2×2 system: QPSK

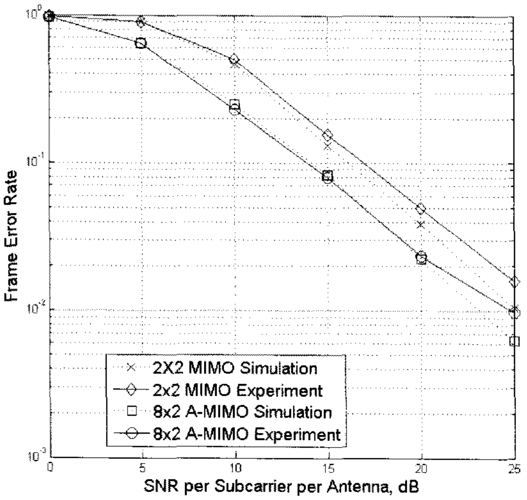


Fig. 5. FER performance comparison between 8×2 and 2×2 system: 16-QAM

outperforms 2×2 system by approximately a 2.6 dB in the SNR and thereis a reduction of 0.5dB in the SNR gain in comparison with the result of QPSK modulation. From the simulation result, it is verified that imperfect channel estimation causes approximately 0.5dB loss in the SNR gain. That's why achievable beamforming gain reduces from 3.12dB to 2.6dB in case of 16QAM modulation case.

Ⅵ. Conclusion

This paper presents an A-MIMO OFDMA signal processing that supports the IEEE 802.16e WMAN standard-based WiBro system. In order to evaluate the downlink performance of an A-MIMO OFDMA system, a fixed-point simulation testbed adopting DSP boards is designed and implemented. In both the experimental and simulation data, the A-MIMO OFDMA system significantly outperformed ordinary MIMO OFDMA system at a given FER. A-MIMO OFDMA system employing QPSK/16-QAM improved the required SNR by approximately 3 dB / 2.5 dB, respectively, compared to ordinary MIMO OFDMA system.

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