심볼 기반의 적응 변조 기법을 이용한 채널 부호화된 MIMO-OFDM 시스템

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Symbol Based Rate Adaptation in Coded MIMO-OFDM Systems

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요 약

다중사용자 무선 채널 환경에서 공간분할 다중접속 기법을 사용함으로서 전체 시스템의 전송률을 대폭 증가시킬 수 있다. 송신단에서 정확한 채널정보를 알고 있는 경우, 전송률을 적절하게 조절함으로서 시스템 성능을 보다 향상시킬 수 있다. 뿐만 아니라, 주파수 선택적 페이딩 특성을 갖는 광대역 무선 채널에서는 채널 부호화를 통해 채널 다이버시티를 활용하여 신뢰성이 높은 데이타 전송이 가능하도록 BIC-OFDM 기술을 사용한다. 본 논문에서는 제한된 궤환정보를 이용한 기회적 스케줄링 기법과 결합된 적응 변조 시스템을 제안하고자 한다. 제안된 기법은 주파수 다이버시티와 다중 사용자 다이버티시를 이용하여 링크 성능을 향상시킬 수 있다. 또한, 적은양의 궤환 정보를 위해 모든 부채널 대신 하나의 OFDM심볼을 기준으로 적응 변조 기법을 사용한다. 모의 실험에서는 본 논문에서 제안한 기법이 적절한 계산복잡도를 가지면서도 상당한 링크 성능 향상이 있음을 보여주고자 한다.

Key Words : Adaptive Modulation and Coding (AMC), Multi-Input Multi-Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), Sapce Division Multiple Access (SDMA) and Dounlink

ABSTRACT

The use of space-division multiple access (SDMA) in the downlink of multiuser multi-input/multi-output (MIMO) wireless transmission systems can provide substantial gains in system throughput. When the channel state information (CSI) is available at the transmitter, a considerable performance improvement can be attained by adapting the transmission rates to the reported CSI. In addition, to combat frequency selective fadings in wideband wireless channels, bit-interleaved coded OFDM (BIC-OFDM) modulation schemes are employed to provide reliable packet delivery by utilizing frequency diversity through channel coding. In this paper, we propose an adaptive modulation and coding (AMC) scheme combined with an opportunistic scheduling technique for the MIMO BIC-OFDM with bandwidth-limited feedback channels. The proposed scheme enhances the link performance by exploiting both the frequency diversity and the multiuser diversity. To reduce the feedback information, the proposed AMC scheme employs rate adaptation methods based on an OFDM symbol rather than on the whole subchannels. Simulation results show that the proposed scheme exhibits a substantial performance gain with a reasonable complexity over single antenna systems.

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Ⅰ. Introduction

In wideband cellular systems, transmitted packets normally experience both time and frequency selective fadings due to user mobility and multipath reflections. Such systems require robust transmission techniques to combat various channel impairments. The frequency selectivity can be mitigated by the combination of orthogonal frequency division multiplexing (OFDM) and bit-interleaved coded modulation (BICM)[1]. The OFDM transforms the frequency-selective fading channel into an equivalent set of several frequency-flat subchannels. As a result, wideband transmission is possible over frequency-selective channels without applying equalizers. In addition, the BICM offers good diversity gains with higher order modulation schemes using binary convolutional codes. The bit-interleaved coded OFDM (BIC-OFDM) which combines the OFDM with the BICM has been applied to a wide range of wireless standards such as the IEEE 802.11a wireless local area network (WLAN)[2].

For spectrally efficient transmissions, much attention has been paid to multi-input/multi-output (MIMO) transmission techniques since a new space-time architecture was introduced by Foschini[3]. It has been shown in [3] that MIMO systems provide multiple independent parallel channels, and thus, the channel capacity increases linearly with the number of antennas. Space-division multiple access (SDMA)[4] involves transmitting independent user streams of data across multiple antennas to maximize throughput. In this paper, we consider the SDMA combined with the BIC-OFDM which delivers multiple user streams simultaneously over the MIMO channels.

For downlink packet transmissions, the signal-to-noise ratio (SNR) at a user equipment (UE) normally varies in time due to the user mobility. If the channel state information (CSI) is known at the transmitter, adaptive modulation and coding (AMC) schemes can improve the link performance by adjusting the transmit power, data rate, and/or coding schemes according to the CSI. The AMC combined with the time domain scheduling offers an opportunity to take advantage of short term variations in fading envelopes of a UE so that the UE is always being served on a constructive fade.

If the CSI can be perfectly known at the transmitter, the MIMO channel can be decomposed into independent parallel subchannels by applying the singular value decomposition (SVD) to the channel matrix. Then, the power and bits on each subchannel can be optimally loaded by the water-filling (WF) technique[5]. However, it is too complex to carry out the SVD and the WF process on all subcarriers in the MIMO-OFDM systems. In addition, the required amount of feedback information (FI) may be too large to be handled in bandwidth limited feedback channels.

In this paper, we propose an AMC scheme for the SDMA system employing the BIC-OFDM. Among all users who attempt to transmit data at the same time slot, the opportunistic scheduler[6] selects user streams to be transmitted through each antenna. For simplicity, we assume that different user streams are assigned for each antenna at the SDMA architecture.

In the proposed scheme, a linear equalizer is employed at the receiver to deal with the interference from other streams. The supportable transmission rates for each stream are determined by utilizing the CSI at the UE side. To minimize the required FI amount, the assigned rate for each stream is fixed for one OFDM symbol. By doing so, the proposed scheme is beneficial for practical systems where the bandwidth for the feedback channel is limited.

This paper is organized as follows: The system model for the MIMO BIC-OFDM is described in section II. In section III, the proposed AMC schemes and the opportunistic user scheduling method will be presented. Finally, the simulation results and the conclusion are presented in sections IV and V, respectively.

Ⅱ. System Model

Fig. 1 shows the system model for the SDMA system employing the BIC-OFDM scheme. We consider the MIMO-OFDM system with N subcarriers transmitting information sequences modulated by the BICM[1]. The BICM achieves diversity gain in the frequency domain through channel coding on frequency selective channels. The BIC-OFDM is constructed by concatenating a binary convolutional encoder with a memoryless mapper through a bit-level interleaver in OFDM systems. After a binary label mapping, symbols are then serial-to-parallel converted and are modulated by the inverse fast Fourier transform (IFFT).

In this paper, we assume that the MIMO channels are spatially uncorrelated and that the number of receive antennas is at least the same as that of transmit antennas. Denote N_t and N_r as the number of transmit antenna and the number of receive antennas, respectively. Then, a total of N_t streams are separated at the output of the linear equalizer at the receiver. For conveniences, we refer to the ith stream as the user data sequence transmitted through the ith transmit antenna. For this scheme, the channel states are supposed to be static during one packet transmission while each transmission experiences different channel states. Also, error-free feedback channels are assumed in this paper.

Assuming that the cyclic prefix (CP) is longer than the channel delay spread, the output at the nth subcarrier at each time slot from the jth receive antenna after the fast Fourier transform (FFT) is given by

$$\mathbf{r}_n = \begin{bmatrix} r_1^n \\ \vdots \\ r_{N_r}^n \end{bmatrix} = \mathbf{H}_n \mathbf{x}_n + \mathbf{z}_n$$
$$= \begin{bmatrix} H_{11}^n & \cdots & H_{N_t 1}^n \\ \vdots & \ddots & \vdots \\ H_{1N_r}^n & \cdots & H_{N_t N_r}^n \end{bmatrix} \begin{bmatrix} x_1^n \\ \vdots \\ x_{N_t}^n \end{bmatrix} + \begin{bmatrix} z_1^n \\ \vdots \\ z_{N_r}^n \end{bmatrix}$$

where H_{ij}^n represents the equivalent channel

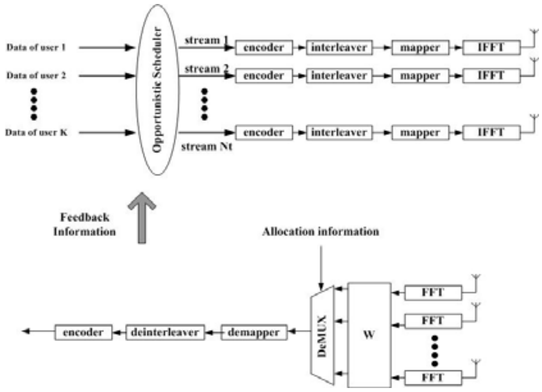

그림 1. 다중안테나 BIC-OFDM 의 기본 구조
Fig. 1 System model for adaptive MIMO BIC-OFDM

frequency response of the link between the ith transmit antenna and the jth receive antenna at the nth subcarrier, z_j^n denotes independent and identically distributed (i.i.d) complex additive Gaussian noise with variance σ_z^2 per complex dimension, x_i^n stands for the transmitted symbol at the ith transmit antenna with variance σ_s^2. The total power of $\mathbf{x}_n$ is assumed to be $P = N_t \cdot \sigma_s^2$ and it is equally distributed over N_t transmit antennas.

Assuming that the channel impulse responses are time invariant during the transmission, the equivalent channel frequency response for the received signal can be expressed by $H_{ij}^n = \sum_{l=1}^{L} \bar{h}_{ij}(l) \exp(-j2\pi nl/N)$ where $\bar{h}_{ij}(l)$ denotes the time domain channel impulse response at the lth tap of the link from the ith transmit antenna to the jth receive antenna, which is independent complex Gaussian with zero mean.

At the transmitter, user data streams to be transmitted through N_t antennas are selected by the opportunistic scheduler where the modulation and coding scheme (MCS) level for each stream is determined by the AMC scheme at the UE side.

Ⅲ. AMC Schemes for SDMA System

In this section, we propose an AMC scheme and an opportunistic scheduling method for the MIMO BIC-OFDM system. We first introduce a linear equalization employed in this paper and then define the signal to interference plus noise ratio (SINR) at the output of the linear equalizer. Based on the noise variance and the SINR, the proposed AMC schemes% for the MIMO BIC-OFDM system will be derived. Finally, the opportunistic scheduling scheme for assigning user streams to N_t antennas will be devised.

3.1 BER Estimation Scheme with Linear Equalizers

Consider that N_t transmitted signals are detected by the linear equalizer matrix $\mathbf{W}_n$. After applying the equalizer, the output at the nth subcarrier $\mathbf{y}_n = \left[y_n^1 \ \cdots \ y_n^{N_t} \right]^T$ can be represented by

$$\mathbf{y}_n = \mathbf{W}_n \mathbf{r}_n = \mathbf{W}_n \left(\mathbf{H}_n \mathbf{x}_n + \mathbf{z}_n \right).$$

Denoting $\mathbf{w}_{n,i}$ and $\mathbf{h}_{n,i}$ as the ith row of $\mathbf{W}_n$ and the ith column of $\mathbf{W}_n$, respectively, the output for the ith stream is given as

$$y_n^i = \mathbf{w}_{n,i} \mathbf{h}_{n,i} x_n^i + \sum_{\substack{r=1 \\ r \neq i}}^{N_t} \mathbf{w}_{n,r} \mathbf{h}_{n,r} x_n^r + \mathbf{w}_{n,i} \mathbf{z}_n$$

where the last two terms in the above equation represent the interference plus noise with the total variance $\sigma_{w,i}^2$ given as

$$\sigma_{w,i}^2 = \sum_{\substack{r=1 \\ r \neq i}}^{N_t} \| \mathbf{w}_{n,r} \mathbf{h}_{n,r} \|^2 \sigma_s^2 + \| \mathbf{w}_{n,i} \|^2 \sigma_z^2 \quad .$$

Then, the SINR at the output of the equalizer for the ith stream at the nth subcarrier can be expressed as

$$SINR_{n,i} = \frac{\| \mathbf{w}_{n,i} \mathbf{h}_{n,i} \|^2 \sigma_s^2}{\sigma_{w,i}^2} = \rho_{n,i} \tag{1}$$

For linear equalizers, two equalization criteria can be considered. Zero-forcing equalizer (ZFE) [7] is the simplest equalizer which applies channel inversion to eliminate the interference from other streams. Using the ZFE criterion, the equalizer matrix $\mathbf{W}_n^{ZFE}$ is obtained as

$$\mathbf{W}_n^{ZFE} = \left(\mathbf{H}_n^H \mathbf{H}_n \right)^{-1} \mathbf{H}_n^{\dagger}$$

where $(\cdot)^H$ denotes the Hermitian transpose.

Although the ZFE is simple to compute, it suffers from noise enhancement. In contrast, minimum mean square error equalizer (MMSE)[7] is more widely used because of its better performance. The MMSE equalizer matrix $\mathbf{W}_n^{MMSE}$ can be obtained as

$$\mathbf{W}_n^{MMSE} = \left(\mathbf{H}_n^H \mathbf{H}_n + \frac{\sigma_n^2}{\sigma_s^2} \mathbf{I}_{N_t} \right)^{-1} \mathbf{H}_n^{\dagger}$$

where $\mathbf{I}_{N_t}$ denotes an $N_t \times N_t$ identity matrix.

The BICM modulation is carried out on each stream with the channel encoder C and M-QAM constellation. For the given encoder C, $R_c(C)$ represents the channel coding rate and $d_H(C)$ stands for the minimum Hamming distance. Throughput this paper, we employ rate compatible punctured convolutional codes (RCPC)[8] where higher rate codes are punctured from the rate 1/2 mother code with the puncturing period p. Denoting the SINR vector as $\Omega_i = \left[\rho_{1,i} \ \cdots \ \rho_{N,i} \right]$, the instantaneous BER for the ith stream can be estimated as[8]

$$BER_i = \frac{1}{p} \sum_{d=d_H(C)}^{d_H(C)+5} N(d) P(d, \Omega_i) \tag{2}$$

where $N(d)$ stands for the total input weight of the error events at Hamming distance d and $P(d, \Omega_i)$ represents the average codeword pairwise error probability (PEP) between the codewords at Hamming distance d. For single carrier systems, the exact computation of

$P(d,\Omega_i)$ is possible if the channel can be modeled as Rayleigh or Rician distribution[1]. In addition, more efficiency computation method for AWGN channels was proposed in [9]. For OFDM systems, however, the exact computation of $P(d,\Omega_i)$ is too complex due to the frequency selectivity of the channel.

To overcome this complexity, we employ a simple BER estimation scheme for single-input/single-output (SISO) case proposed in [10]. When we apply that scheme with the SINR vector Ω_i for each stream, $P(d,\Omega_i)$ can be obtained as

$$P(d,\Omega_i) \le \frac{1}{m^d} \sum_{\underline{S}} \prod_{k=1}^{d} \frac{1}{2^{(m-1)}} \sum_{x_k \in \chi_0^j} \sum_{v_k \in \chi_1^j} P(x_k \to v_k \mid \rho_{k,i})$$

$$= \overline{B}_{M,i} \tag{3}$$

where χ_b^j denotes a subset of signal points in M-QAM constellation whose jth bit is b, and $m=\log_2 M$. Assuming ideal interleaving and Gray mapping, Eq. (3) can be rewritten as

$$\overline{B}_{M,i} = \prod_{k=1}^{d} E_{\rho_{k,i}} \left[\frac{1}{m2^{m-1}} \sum_{j=1}^{m} \sum_{x_k \in \chi_0^j} \sum_{v_k \in \chi_1^j} P(x_k \to v_k \mid \rho_{k,i}) \right]$$

$$= \left(\frac{1}{N} \sum_{k=1}^{N} \frac{1}{m2^{m-1}} \sum_{j=1}^{m} \sum_{x_k \in \chi_0^j} \sum_{v_k \in \chi_1^j} P(x_k \to v_k \mid \rho_{k,i}) \right)^d$$

$$= \left(\frac{1}{N} \sum_{k=1}^{N} B_M(\rho_{k,i}) \right)^d \tag{4}$$

The most likely error events in computing (4) corresponds to the erroneous decision v_k as one of neighboring points around x_k, whose jth bit is different from x_k. Thus further simplification is possible as in [10]. Fig. 2 shows an example

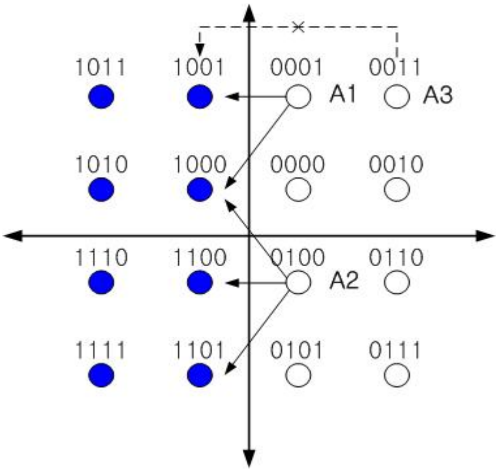

그림 2. 16QAM 신호의 근접격자점 (j=1)
Fig. 2 Neighboring points of 16-QAM signal set with Gray mapping (j=1)

of 16-QAM constellation with j=1. The shaded circles represent a set of points whose 1st bit position is 1. There are three types of transitions characterizing each error event. Point A1 has two neighboring points which differ at the 1st bit position, whereas A2 has three such neighboring points. On the other hand, A3 does not have any neighboring points which differ at the 1st bit position. Note that there are four such points for j=1 and 2, while there exist no point which can be classified as A3 for j=3 and 4.

Denoting Q_1 and Q_2 as

$$Q_1 = Q\left(\sqrt{\frac{1.5\rho_{n,i}}{M-1}}\right) \quad \text{and} \quad Q_2 = Q\left(\sqrt{\frac{3\rho_{n,i}}{M-1}}\right),$$

respectively, $B_M(\rho_n)$ for 16-QAM constellation can be computed as $3(2Q_1+3Q_2)/8$ considering for all j. Here, $Q(x)$ is defined as $\frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-z^2/2} dz$ and can be approximated by [11]

$$Q(x) \approx \frac{1}{x(1-(1/\pi)) + (1/\pi)\sqrt{x^2+2\pi}} \frac{1}{\sqrt{2\pi}} e^{-x^2/2}.$$

Similarly, $B_M(\rho_{n,i})$ values for QPSK and

64-QAM can be computed as Q_1+Q_2 and $(28Q_1+49Q_2)/48$, respectively[10]. As $B_M(\rho_{n,i})$ is readily computed as a function of $\rho_{n,i}$, the BER computation becomes quite simple.

3.2 Rate Adaptation Schemes with Multiuser Scheduling

In this subsection, we propose an AMC scheme and scheduling methods for the MIMO BIC-OFDM system. At each transmission, the transmission rate is selected from the AMC table which defines the modulation and coding schemes for each MCS level. Suppose that the kth user transmits data streams through the ith transmit antenna and the AMC table supports a total of l_{max} MCS levels. Each MCS level l (l=1,...,l_{max}) consists of a channel encoder C_l with a rate $R_c(C_l)\in\{R_1 \ \cdots \ R_V\}$, and the M_l-QAM signal set of size $\log_2 M_l \in \{1 \ \cdots \ m_{\max}\}$. The spectral efficiency supported by the MCS level l can be obtained as $R_T(l)=R_c(C_l)\log_2 M_l$. With the given SINR vector Ω_i, we define a cost function for the spectral efficiency $R_T(l)$ as

$$\overline{BER}(\Omega_i,l)=\frac{1}{p_l}\sum_{d=d_H(C_l)}^{d_H(C_l)+5} N_l(d)\,Q\left(\sqrt{-2\log \bar{B}_{M,i}}\right) \quad (5)$$

where p_l denotes the puncturing period of the code. Here, we employ the error bound using the Gaussian approximation in [9] which provides a tighter bound than the standard Bhattacharyya union bound as in [1].

For determination of the MCS level, we consider two criteria. One is a rate decision method with a BER constraint. In this case, the AMC scheme adapts the transmission rate according to the current channel state, while maintaining the average error rate below the required error level. The other MCS selection scheme is a rate maximization scheme which attempts to maximize the total throughput irrespective of the average BER at the receiver.

For the AMC scheme with the BER constraint, the rate adaptation problem can be reformulated as

$$\text{maximize} \quad R_T(l)=R_c(C_l)\log_2 M_l$$

$$\text{subject to} \quad \overline{BER}(\Omega_i,l)\le P_e$$

where P_e denotes the required error rate.

For the rate maximizing AMC scheme, we introduce another cost function which represents the expected throughput at the receiver. The expected throughput can be computed using (5) as

$$R_i(\Omega_i,l)=R_c(C_l)\log_2 M_l\left(1-\overline{BER}(\Omega_i,l)\right)$$

Then, the MCS level for the packet transmission is determined by one which maximizes $R_i(\Omega_i,l)$. This type of the rate adaptation is appropriate for the best effort service such as world wide web (www) or file transfer protocol (FTP), while the AMC scheme with the BER constraint is adequate for reliable per-user transmission by reducing the probability of invoking the congestion control mechanism at the internet protocol (IP) layer.

From now on, we consider multiuser environments to exploit multiuser diversity[12]. The multiuser diversity gain increases with the number of users simultaneously accessing the base station (BS). For simplicity, in this paper, all users are assumed to have the same statistics for channel conditions such as the received SNR.

Suppose that K users attempt to access the BS and each user has sufficient data streams in its waiting queue. Let $R_{k,i}$ denote the supportable data rate at the ith transmit antenna at the user k (k=1,...,K). By the greedy scheduling[13], the BS selects a user with the highest $R_{k,i}\left(1-\overline{BER}_{k,i}\right)$ among all the data rates reported from every users for the ith transmit antenna. Extension to the proportional fair (PF) scheduling[6] is straightforward. The PF scheduling algorithm utilizes asynchronous channel variations by selecting users with the maximum value of $R_k / R_{avg,k}$ where R_k represents $\max_i R_{k,i}(1-\overline{BER_{k,i}})$ and $R_{avg,k}$ denotes the moving average of the data rates at which the user has been served in the previous time slots. This scheduler assigns the transmission to the user with the best channel condition, while providing approximately the same number of time slots to all users.

A total of $N_t \cdot R_{k,t}$ data rates and $N_t \cdot \overline{BER_{k,i}}$ values should be computed at the user side and these values are sent back to the BS. When sufficient users request packet transmissions simultaneously, it can be assumed that at each antenna, there exists at least one user who wants to transmit packets. In this case, the amount of FI can be reduced by only reporting the maximum of $R_{k,i}(1-\overline{BER_{k,i}})$ for i=1,...,N_t along with the chosen antenna index.

Ⅳ. Simulation Results

In this section, we present simulation results for the proposed method. We consider the OFDM system with N=64 subcarriers and the cyclic prefix length is set to 16 samples. A 5 tap exponentially decaying channel profile is assumed for all users and the total transmitted power P is set to be 2. The AMC table used for simulations is listed in Table 1. For the channel encoding, a 64 state punctured convolutional code is employed. When computing the BER estimation in (2), we use $N^*(d)$ values for each channel code tabulated in [14]. Over 10,000 frame transmissions are simulated to measure the system throughput. In evaluating the performance of each AMC scheme, we adopt the "goodput"[15] to measure the system throughput by counting information bits in decoded frames with correct cyclic redundancy check (CRC) in the automatic repeat request (ARQ) mechanism.

표 1. 모의실험용 AMC 테이블
Table 1. AMC Table for simulation

l	$R_T(l)$	R_c	Modulation
1	0.75bps/Hz	3/4	BPSK
2	1bps/Hz	1/2	QPSK
3	1.5bps/Hz	3/4	QPSK
4	2bps/Hz	1/2	16-QAM
5	2.5bps/Hz	5/8	16-QAM
6	3bps/Hz	3/4	16-QAM
7	3.5bps/Hz	7/12	64-QAM
8	4bps/Hz	2/3	64-QAM
9	4.5bps/Hz	3/4	64-QAM
10	5bps/Hz	5/6	64-QAM

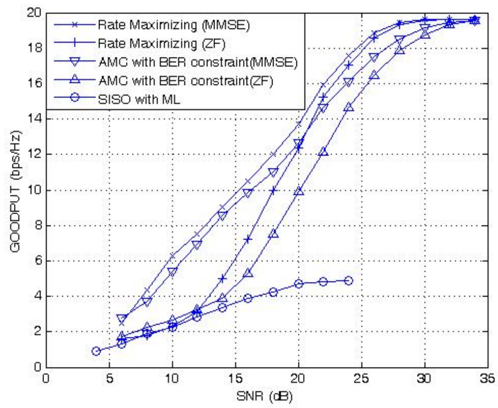

그림 3. 제안된 시스템의 전송률 (N_t=N_r=4)
Fig. 3 Throughput of the proposed system with N_t=N_r=4

Fig. 3 shows the goodput of the proposed scheme with N_t=N_r=4. Here, we assume that K=20 users attempt to transmit packets simultaneously. As shown in the figure, the rate maximizing criterion exhibits higher transmission rates although the required average error rate is not satisfied. For each rate adaptation criterion, the MMSE equalization shows a better performance than the ZFE case as expected. For the ZFE, the computed SINR at the output of the linear equalizer is inferior due to the noise enhancement[7]. Thus the selected data rate is normally less than that of the MMSE case since the proposed AMC scheme determines the MCS level index as a function of the SINR. In general, the required SNR to increase a unit spectral efficiency satisfying the BER constraint grows as the desired spectral efficiency becomes higher. This yields that the expected BER of the determined MCS level employing the AMC scheme with BER constraints is readily too much lower than the required BER at higher spectral efficiencies. In these regions, the rate maximizing AMC scheme can enhance the throughput by considering only the expected throughput among the AMC set. As shown in the figure, at higher data rate regions around 90% of the maximum achievable rate, the performance gap between two rate adaptation schemes is larger than the gap at the relative low spectral efficiency region. In addition, since the ZFE requires more SNR to select higher spectral efficiency, the ZFE exhibits the more performance improvement than the MMSE case by employing the rate maximizing AMC. For comparison, we also plot the AMC result with the multiuser environment in the SISO case. In this case, we employ a maximum likelihood demapper instead of linear equalizers. As expected, the spatial multiplexing scheme shows the superior performance and the performance gain over SISO cases grows as the SNR increases.

V. Conclusion

In this paper, we propose the AMC and scheduling schemes for the downlink SDMA system for the BIC-OFDM. The proposed scheme employs the linear equalizer at the receiver to detect the transmitted symbols with lower complexity. The proposed scheme can exploit the multiuser diversity by assigning different users to each antenna with the opportunistic scheduling. Simulation results show that the proposed scheme exhibits a substantial performance gain with reasonable complexity over the single antenna case. This scheme is beneficial for practical systems where the bandwidth for the feedback channel is limited.

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