제한된 궤환정보를 이용한 다중사용자 BIC-OFDM

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Multiuser Bit-Interleaved Coded OFDM with Limited Feedback Information

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요 약

무선 접속 시스템에서는 주파수 선택적 페이딩 환경에서 직교 주파수 분할 다중화 기법 (OFDM)의 성능을 향상시키기 위한 연구가 많이 진행되었다. 시불변 채널을 송수신단 모두 알고 있는 경우, 워터 필링 (water-filling) 기법을 이용한 적응변조 기법이 최적이라고 증명되었다. 하지만, OFDM 시스템에서는 워터 필링 기법은 모든 부채널에 대한 채널정보를 송신단으로 보내기 위한 방대한 양의 오버헤드를 필요로 하게 된다. 본 논문에서는 제한된 궤환정보를 이용한 하향링크 적응변조 및 부호화 기법에 대해 제안하고자 한다. 궤환정보의 양을 최소화하기 위해서 각 부채널에 대한 채널정보 대신 하나의 OFDM 심볼을 기준으로 한 적응변조 방법을 적용한다. 궤환정보의 양이 대폭 감소되었지만, 성능열화 정도는 2dB 보다 적게 나타남을 모의실험을 통해 확인하고자 한다. 또한, OFDM 시스템에서는 부채널들을 그룹화하여 다중사용자 환경에서 사용될 수 있다. 이러한 다중사용자 환경에서는 본 논문에서 제안하는 기법의 전송률이 부채널 그룹이 증가할수록, 그리고 사용자가 많아질수록 채널용량에 근접함을 보여주고자 한다.

Key Words : Bit-Interleaved Coded Modulation (BICM), Orthogonal Frequency Division Multiplexing (OFDM), Adaptive Modulation and Coding (AMC), Limited Feedback and Multiuser

ABSTRACT

In wireless access systems, there has been much interest in enhancing the performance of orthogonal frequency division multiplexing OFDM) in a frequency selective fading channel. If the channel is static and is perfectly known to both the transmitter and the receiver, the water-filling technique with adaptive modulation is known to be optimal[1]. However, for OFDM systems, this requires intensive traffic overheads for reporting channel side information on all subcarriers to the transmitter. In this paper, we propose an adaptive modulation and coding scheme for bit-interleaved coded OFDM (BIC-OFDM) for downlink packet transmissions with reduced feedback information. To minimize the feedback information, we employ a rate adaptation method based on the OFDM symbol rather than on each subcarrier. To illustrate the performance gap between the optimal water-filling and the proposed scheme, we will compare cutoff rates for both schemes. It is shown that the loss is less than 2dB while the proposed scheme significantly reduces the feedback payloads. Also, the OFDM system in multiuser environment with subcarrier grouping is considered. It is shown that by exploiting multiuser diversity the throughput of the proposed scheme approaches the channel outage capacity as the number of users and the number of subcarrier groups increase.

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Ⅰ. Introduction

For high speed wireless packet communication systems, we need to combat the intersymbol interference caused by frequency selective channels. By using Orthogonal Frequency Division Multiplexing (OFDM), wideband transmission is possible over frequency selective fading channels without applying equalizers. In addition, bit-interleaved coded modulation (BICM) offers good diversity gains with higher order modulation schemes using binary convolutional codes[2]. Bit-interleaved coded OFDM (BIC-OFDM) which combines the OFDM system with the BICM has been applied to a wide range of wireless standards such as IEEE 802.11a wireless local area network (WLAN)[3].

When the channel is assumed to be quasi-static, adaptive modulation and coding (AMC) is a powerful technique to enhance the link performance for packet transmission systems[4]. The basic idea behind the adaptive transmission is to adapt the transmission power level, channel coding rate and/or constellation size to the current channel state. In the OFDM case, the water-filling with adaptive modulation is known to be optimal if the channel side information (CSI) is perfectly known to the transmitter[1]. However, this requires intensive traffic overheads for the feedback channel to report either the CSI or bit loading information on all subcarriers to the transmitter.

In this paper, we propose an AMC scheme for the BIC-OFDM system which requires reduced feedback information (FI) for downlink packet transmissions. The proposed scheme significantly reduces the amount of the feedback payloads by employing a rate adaptation scheme based on the individual OFDM symbol rather than on each subcarrier. With the proposed scheme, each user equipment (UE) computes the maximum achievable spectral efficiency based on the instantaneous channel capacity over one OFDM symbol and reports the selected modulation and coding scheme (MCS) level index for the corresponding spectral efficiency.

To evaluate the performance loss compared with the optimum system with full FI, we first analyze cutoff rates for both the proposed scheme and the optimum water-filling (WF) scheme. We will show in the simulation section that the performance of the proposed scheme comes within 2dB of the WF scheme while significantly reducing the amount of FI.

Next, we consider a multiuser environment where the bandwidth efficiency is defined as the number of users that can be supported simultaneously per cell [5]. It is clear that by reducing the FI amount the bandwidth efficiency for multiple access system improves. Therefore, the proposed scheme allows us to accommodate more users than the WF scheme with the same bandwidth efficiency. In addition, the subchannel grouping further enhances the system throughput by decreasing the probability that symbols are transmitted in deep fadings.

The paper is organized as follows: In section Ⅱ, the system model for the proposed adaptive BIC-OFDM is presented. The proposed AMC scheme with reduced FI is presented in section Ⅲ In this section, we illustrate a simple rate decision scheme and provide the cutoff rate of adaptive BIC-OFDM systems. Then, we extend the proposed rate adaptation scheme to the multiuser environment by employing subcarrier grouping. Finally, the simulation results and conclusion are presented in section Ⅳ and Ⅴ, respectively.

Ⅱ. System Model

We consider an OFDM system with N subcarriers transmitting information sequences modulated by BICM[2]. The BICM achieves the diversity gain in the frequency domain through channel coding. The BIC-OFDM is constructed by concatenating a binary convolutional encoder with a memoryless mapper through a bit-level interleaver. After a one-to-one binary labeling map, symbols in M-QAM are then serial-to-parallel converted and modulated by the inverse Fourier transform (IFFT) block.

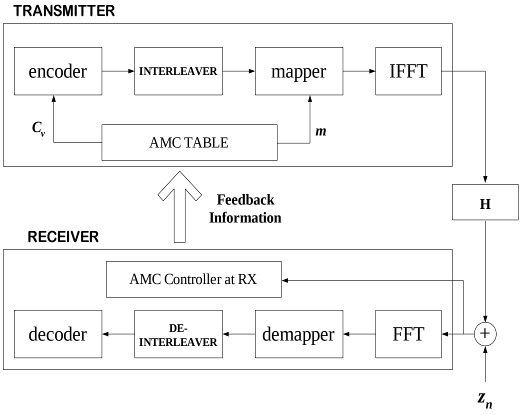

그림 1. 적응변조 BIC-OFDM 시스템
Fig. 1 System model for the adaptive BIC-OFDM

Figure 1 shows the system model of the adaptive BIC-OFDM systems. As shown in the figure, the transmission rates and power levels are controlled

based on the FI obtained at the receiver. For the proposed rate adaptation scheme, the MCS level is determined by the AMC controller at the receiver with the constraint of the fixed transmit energy E_S on all subcarriers. Each MCS level l $(l=1,\cdots,l_{\max})$ consists of a convolutional encoder, $C^*(l)\in\{C_1 \ \cdots \ C_V\}$ and the $M(l)$-QAM signal set with $m(l)=\log_2 M(l)\in\{1,\cdots,m_{\max}\}$ where $M(l)$ denotes the QAM constellation size of the lth MCS level. Since the proposed rate adaptation scheme is based on one OFDM symbol, the required FI reduces to the determined MCS level index only. For the MCS level l, the spectral efficiency can be written as $R_T=R_c(l)\mathrm{log2}M(l)$ (bps/Hz) where $R_c(l)$ enotes the coding rate of the channel encoder $C^*(l)$.

With FFT at the demodulation, the received signal at the \$n\$th subcarrier at the ith time slot after removing the cyclic prefix (CP) is given by $y_{n,i} = H_{n,i}\, s_{n,i} + z_{n,i}$ where $s_{n,i}$ is the transmitted signal at the nth subcarrier, $z_{n,i}$ denotes an independent, identically distributed (i.i.d) complex additive Gaussian noise with variance σ^2 per complex dimension and $H_{n,i}$ represents the equivalent channel frequency response.

In this channel model, we make the following assumptions. Considering the time domain channel impulse response from the transmitter to the receiver, a frequency selective fading channel can be modeled as

$$h(t,\tau)=\sum_{p=0}^{L-1}\bar{h}(p;t)\delta(\tau-\tau_p) \qquad (1)$$

where the channel coefficient $\bar{h}(p;t)$ are independent complex Gaussian with zero mean (Rayleigh fading), τ stands for the propagation delay for the pth channel tap, L denotes the number of channel taps, and $\delta(\cdot)$ represents the Dirac delta function.

Both fast fading (i.e. uncorrelated fading coefficients in time) and block fading (i.e. static fading coefficients over a block of transmitted symbols, independent over blocks) are possible for this channel model. For the adaptive transmission, the CSI is assumed to remain unchanged during one packet transmission. Hence, we will concentrate on the block fading model and omit the time indices i and t for simplicity. This gives rise to the channel frequency response at the nth subcarrier can be written as

$$H_n=\sum_{p=0}^{L-1}\bar{h}(p)\exp\left(-j\frac{2\pi n\tau_p}{NT}\right)$$

where $\bar{h}(p)$ denotes the pth tap of the channel response from the transmitter to the receiver and T represents the sampling period. Note that $|H_n|$ is Rayleigh distributed and is correlated in frequency. Throughout this paper, we assume that the CSI is perfectly known at the UE side. Also, we consider a single cell system, thus neglect the interference from neighboring cells.

At the receiver in Fig. 1, the maximum likelihood (ML) soft bit metrics for the received symbol y_n are computed by the demapper. These values are de-interleaved and used as the input to the channel decoder to determine the transmitted information sequence.

Ⅲ. Adaptive BICM System with Reduced FI

In this section, we propose an AMC scheme for the BIC-OFDM with reduced FI. We first propose a rate adaptation scheme and then consider a multiuser scheduling with subcarrier grouping to exploit the multiuser diversity.

3.1 Rate Adaptation Scheme for BIC-OFDM Systems

The proposed scheme utilizes the channel capacity with a given channel realization. The instantaneous channel capacity of the OFDM system with N subcarriers can be expressed as

$$\hat{C} = \frac{1}{N}\sum_{n=0}^{N-1}\log_2\left(1+\frac{E_s}{\sigma^2}|H_n|^2\right) \qquad (2)$$

The rate adaptation problem in this paper is equivalent to maximization of spectral efficiencies subject to the fixed transmission power and rate on all subcarriers. The instantaneous capacity represented in (2) provides the maximum achievable transmission rate for given channel responses. For the proposed scheme, the UE determines the transmission rates by averaging the instantaneous channel capacity with a constant channel gap Γ [6]. Define $R^* = \{R_1, \cdots, R_{l_{\max}}\}$ as a set of all possible spectral efficiencies in the AMC table which is constructed from channel code rates and modulation levels. First, UE determines the transmission rate for given $\mathbf{H} = \{H_0, \cdots, H_{N-1}\}$ as

$$R(\mathbf{H}) = \arg\min_{R_l \in R^*}\left|R_l - \frac{1}{N}\sum_{n=0}^{N-1}\log_2\left(1+\frac{E_s|H_n|^2}{\sigma^2\Gamma}\right)\right|$$

where the average symbol energy for each M-QAM constellations is normalized as E_s.

Then, the UE reports the MCS level index corresponding to the determined rate $R(\mathbf{H})$ to the BS. Based on this information, the BS generates physical layer frames with selected code rates and modulation levels. Due to the frequency selectivity of the channel, the received symbols at each subcarrier normally exhibit different received signal to noise ratios (SNR). The BIC-OFDM mitigates the fluctuation by employing the AMC over the OFDM symbol.

For the proposed scheme, the amount of required FI is only $\lceil \log_2 l_{\max} \rceil$ bits, irrespective of N, which is the number of bits required to represent one of $l_{\max}$ MCS levels. Here, $\lceil a \rceil$ denotes the smallest integer no less than a. In contrast, for the WF case, the amount of FI increases as the number of subcarrier increases. Assuming that the water-filling optimization is carried out at the UE side, the WF scheme requires $N\left(\lceil \log_2 m_{\max} \rceil + N_q\right)$ bits in total for the amount of FI in the uncoded case where N_q denotes the number of bits to represent the quantized power level.

Now, to compare the theoretical performance of the proposed scheme with that of the optimal WF scheme, we analyze channel cutoff rates for both adaptation schemes. The cutoff rate provides a practical achievable information rate when employing a finite complexity detection scheme. The cutoff rate of a BICM scheme can be computed from the Bhattacharyya bound on the average bit error probability of the parallel channel model[2] in the absence of coding[7]. Theoretically, the cutoff rates can be obtained as the ergodic average of the instantaneous cutoff rates in i.i.d. fading channels with an infinite length interleaver to satisfy the assumption of the parallel channel model. In contrast, for the BIC-OFDM, the transmitted symbols for each subcarrier experience correlated fadings in frequencies. Therefore, the cutoff rate of BIC-OFDM should be computed by averaging the instantaneous cutoff rate over one OFDM symbol[8].

The instantaneous cutoff rate R_0 of a discrete-time channel generated by the BIC-OFDM with M-QAM can be written as [9]

$$R_0(\mathbf{H}) = m\left(1-\log_2\left(1+E_b\left[P\left(b\to\bar{b}\mid b,\mathbf{H}\right)\right]\right)\right) \qquad (3)$$

where $m=\log_2 M$.

For the ideal water-filling, the number of bits loaded in the nth subcarrier, $m_n(H_n)$, can be determined by

$$m_n(H_n) = \left\lfloor \log_2\left(1+\frac{E_s\,|H_n|^2}{\sigma^2}\right)\right\rfloor$$

where $\lfloor a \rfloor$ indicates the largest integer not exceeding a. Denote $\chi^{i}_{m,b}$ as a set of M-QAM signals whose ith bit is b ($i \in \{1,\cdots,m\}$, $b \in \{0,1\}$). By employing the Bhattacharyya union bound to represent the transition error probability in (3), the instantaneous cutoff rate for the WF scheme can be expressed as

$$R_0^{WF}(\mathbf{H}) = \frac{1}{N}\sum_{n=0}^{N-1} m_n(H_n)\Big(1-\log_2\big(1+B\big(H_n, m_n(H_n)\big)\big)\Big)$$

where the Bhattacharyya factor $B\big(H_n, m_n(H_n)\big)$ is computed by

$$B\big(H_n, m_n(H_n)\big) = \frac{1}{m}\sum_{i=1}^{m} E_{b,y}\left[\sqrt{\frac{\sum_{z\in\chi^{i}_{m,\bar{b}}} P(y\,|\,z,H_n)}{\sum_{z\in\chi^{i}_{m,b}} P(y\,|\,z,H_n)}}\right].$$

In contrast, for the proposed scheme, the number of bits loaded on each subcarrier is set to be the same over one OFDM symbol. For the ideal case, the maximum achievable spectral efficiency can be written as

$$\tilde{m}_n(H_n) = \left\lfloor \frac{1}{N}\sum_{n=0}^{N-1}\log_2\left(1+\frac{E_s\,|H_n|^2}{\sigma^2}\right)\right\rfloor.$$

Then, the instantaneous cutoff rate R_0^{AMC} for the proposed scheme is given by

$$R_0^{AMC}(\mathbf{H}) = \tilde{m}_n(H_n)\frac{1}{N}\sum_{n=0}^{N-1}\Big(1-\log_2\big(1+B\big(H_n, \tilde{m}_n(H_n)\big)\big)\Big).$$

3.2 Multiuser Scheduling with Subcarrier Grouping

Now, we consider multiuser environments to exploit the multiuser diversity[10]. The multiuser diversity gain increases with the number of users simultaneously accessing the BS. Since the required FI for the proposed scheme is only the selected MCS level index, a larger number of UE's can report the FI using the bandwidth allocated for the feedback channel. In this case, the multiuser diversity can be obtained by an opportunistic scheduling[10]. For simplicity, in this paper, all users are assumed to have the same statistics for channel conditions.

Suppose that K users are in a cell and each user has sufficient data stream in its waiting queue. Let R_k denote the data rate requested by the user k. By a greedy scheduling[11], the BS selects a user with the highest R_k among all the data rates reported from every users. Extension to the proportional fair scheduling proposed in [12] is straightforward. The proportional fair scheduling algorithm utilizes asynchronous channel variations by selecting users with the maximum value of $R_k / R_{avg,k}$ where $R_{avg,k}$ denotes the moving average of the data rate 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.

Now, in order to further improve the performance of the multiuser scheduling, we propose a method of subcarrier grouping. By dividing the whole subcarrier into several groups and allocating each subcarrier group to the users with the most favorable channel condition, the probability that symbols experience deep fadings reduces as the number of groups increases. Therefore, performance can be improved by avoiding the transmission through subcarriers with unfavorable channel conditions.

To this end, total N subcarriers are divided into G groups. Denoting G^{*}_{g} as a set of the predetermined subcarriers assigned for the *g*th group ($g=0,1,\cdots,G-1$), the *k*th user computes the achievable data rate $\tilde{R}_{k,g}$ for all groups as

$$\tilde{R}_{k,g} = \arg\min_{R_l} \left| R_l - \frac{G}{N} \sum_{n \in G_g^*} \log_2 \left(1 + \frac{E_s \mid H_n^k \mid^2}{\sigma^2 \Gamma} \right) \right|$$

where H_n^k represents the channel frequency response at the *n*th subcarrier of the *k*th user. Here, we assume that the number of subcarriers in each group is the same for simplicity. Then, UE reports the determined MCS level index for all groups corresponding to $\tilde{R}_{k,g}$ to the BS. At the BS, the user to transmit a packet on the *g*th subcarrier group is selected by the one with the maximum $\tilde{R}_{k,g}$. In this case, the required FI amount for K users becomes $\lceil \log_2 l_{\max} \rceil \times G \times K$. This is still much less than the FI amount required for the WF scheme. When sufficient users request packet transmissions simultaneously, it can be assumed that at each subcarrier group, there exists at least one user who wants to transmit packets. In this case, the FI amount can be further reduced by reporting only the best MCS level among all subcarrier groups at each user. By doing this, the amount of FI considering K users reduces to $\left(\lceil \log_2 l_{\max} \rceil + \lceil \log_2 G \rceil \right) \times K$.

Considering the multiuser scheduling for the WF scheme, the WF process can be performed by either the BS or the UE. When the base station performs the WF process, the required FI is increased by K times compared to that of the single user case. This amount of FI may be too large to be handled in practical systems due to the limited bandwidth for the feedback channel. In contrast, if the WF process is performed at the UE and reports the loading information on subcarriers, it is difficult to control the transmit power constraint since each UE does not know the bit and power loading information for other users. Therefore, the multiuser scheduling with the WF scheme may be inappropriate for the system with bandwidth limited feedback channels. In contrast, as the proposed scheme does not need to perform the WF process, it can be easily applied to practical multiuser environments.

표 1. 모의 실험용 AMC 테이블
Table 1. AMC Table for simulation

l	R_l	R_c	Modulation
1	1 bps/Hz	1/2	QPSK
2	2 bps/Hz	1/2	16-QAM
3	3 bps/Hz	3/4	16-QAM
4	4 bps/Hz	2/3	64-QAM
5	4.5 bps/Hz	3/4	64-QAM
6	5 bps/Hz	5/6	64-QAM

Ⅳ. Simulation Results

In this section, we present simulation results for the proposed method. We consider the OFDM system with N=512 subcarriers and the cyclic prefix length is set to 128 samples. A 5 tap exponentially decaying channel profile is assumed for all users. The AMC table used for simulations is listed in Table 1.

For the channel coding scheme, a 64 state punctured convolutional code is employed where higher rate codes are obtained by puncturing the R_c=1/2 mother code[13]. Over 10,000 frame transmissions are simulated to measure the system throughput. In evaluating the performance of each AMC scheme, we adopt the "goodput" 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[14].

In Fig. 2, we exhibit cutoff rates of the proposed scheme and the ideal WF scheme. Here, the maximum modulation level is set to M=64. As shown in the figure, the performance loss is relatively small, while the proposed scheme significantly reduces feedback payloads. The proposed scheme shows about 2 dB loss compared with the WF scheme at the spectral efficiency of 2.5 bps/Hz.

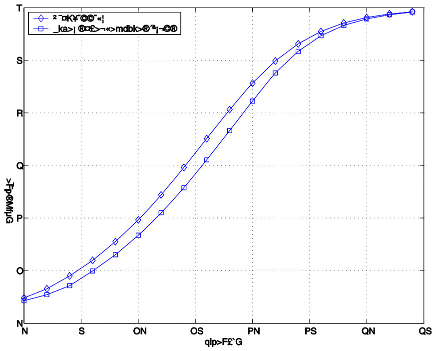

그림 2. 최적의 워터필링과 제안한 시스템의 cutoff rate 비교
Fig. 2 Cutoff rate for the proposed scheme and the optimal water-filling

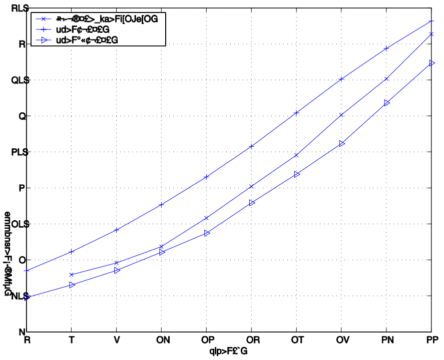

그림 3. 제안하는 시스템의 성능 분석
Fig. 3 Performance for the proposed scheme

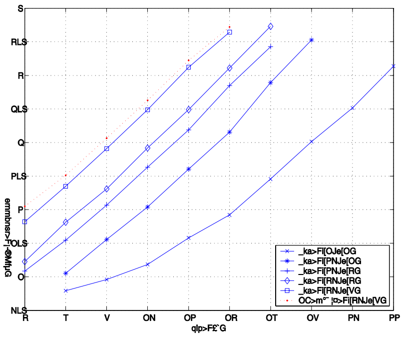

그림 4. 사용자 수와 그룹에 따른 성능 분석
Fig. 4 Effect of the number of users and groups

Fig. 3 shows the goodput in the single user case. For comparison, we also plot the results of the WF schemes both in the uncoded and the coded cases. For the coded case, we illustrate the result of the adaptive BIC-OFDM proposed in [15] which performs the Levin-Campello algorithm to obtain the bit loading on each subcarrier with modified channel gap Γ considering the minimum free distance of the convolutional code. For the proposed scheme, the channel gap Γ is set to be 8 dB to satisfy the 1% frame error rate. As shown in the figure, the proposed scheme shows the performance loss of about 2 dB at the spectral efficiency of 2.5 bps/Hz, which is consistent with the result of Fig. 2. It should be, however, noted that the amount of feedback reduces to the MCS level index. Employing the AMC table in Table **I**, only 3 bits of FI are sufficient for the proposed scheme, while 512 × (2+6)=4096 bits should be reported for the uncoded WF scheme if N_q=6 bits are assumed to quantize the power level for each subcarrier.

Since the required FI for the proposed scheme is significantly reduced, a larger number of users can share the bandwidth allocated for the feedback channel.

In Fig. 4, we plot the performance of the proposed scheme with the greedy scheduling with the subcarrier grouping to illustrate the performance in the multiuser case. As can be seen in this plot, dividing the whole subcarrier into several groups exhibits significant performance gains. Thus the proposed schemes show considerable improvements in terms of the goodput by accommodating multiple users and thus approach the 1% outage capacity as K and G increases.

V. Conclusion

In this paper, we propose an AMC scheme for the BIC-OFDM system which can reduce feedback control channel overheads significantly. The reduced FI improves the overall system bandwidth efficiency, thus a larger number of users can be accommodated with the same bandwidth efficiency. In addition, we propose a subcarrier grouping based multiuser scheduling scheme utilizing the proposed AMC scheme. Simulation results show that the proposed methods exhibit considerable performance improvements with a reasonable complexity.

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