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Cross-layer design based on RC-LDPC codes in MIMO channels with estimation errors

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Abstract

In this paper, we propose a cross-layer design framework combining adaptive modulation and coding (AMC) with hybrid automatic repeat request (HARQ) based on rate-compatible low-density parity-check codes (RC-LDPC) in multiple-input multiple-output (MIMO) fading channels with estimation errors. First, we propose a new puncturing pattern for RC-LDPC codes and demonstrate that the new puncturing pattern performs similar to the random puncturing but is easier to apply. Then, we apply RC-LDPC codes with the new puncturing pattern to the cross-layer design combing AMC with ARQ over MIMO fading channels and derive the expressions for the throughput of the system. The effect of channel estimation errors on the system throughput is also investigated. Numerical results show that the joint design of AMC and ARQ based on RC-LDPC codes can achieve considerable spectral efficiency gain.

Keywords: Rate-compatible LDPC codes; Adaptive modulation and coding (AMC); Automatic repeat request (ARQ); Cross-layer design; Multiple-input multiple-output (MIMO) channel

1. Introduction

The explosive growth of wireless packet data applications such as wireless Internet, interactive mobile multimedia applications, and interactive gaming has driven an unprecedented revolution in wireless networks. Various applications in wireless networks require different quality of service (QoS). In order to achieve efficient utilization of scarce radio resources with different QoS requirements, the cross-layer design approach has drawn significant research attention allowing information sharing between different layers of wireless networks. In the literature, various cross-layer design schemes have been proposed. In [1], adaptive modulation and coding (AMC) at the physical layer and automatic repeat request (ARQ) at the data link layer were jointly designed in order to maximize network capacity under constrained QoS requirements. However, perfect channel state information (CSI) was assumed and only single input single output (SISO) scenario was considered in [1]. This observation motivates us to extend the cross-layer design in SISO channels to multiple-input multiple-output (MIMO) channels using space–time block codes (STBCs) with channel estimation errors.

It is widely accepted that powerful error control codes should be employed to guarantee the high reliability of

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wireless communication systems. Due to the special structure that enables simple encoding and decoding, rate-compatible (RC) codes have been shown to be favorable in both AMC and hybrid ARQ (HARQ) schemes. A RC code consists of a low rate mother code and several higher rate codes achieved through compatible puncturing. Hence, the decoder for the lowest rate code is compatible with the ones for higher rate codes and therefore no additional complexity is needed. In most AMC or HARQ schemes, RC punctured convolutional codes (RCPC) [2] or RC punctured turbo codes (RCPT) [3] were employed as the forward error control codes. Recently, RC low-density parity-check (RC-LDPC) codes [4,5] have raised a lot of research interests, e.g., finding the optimal puncturing pattern [6] and applying RC-LDPC codes to HARQ [5]. To the best of the authors' knowledge, however, there has not been any report on the application of RC-LDPC codes to cross-layer design schemes. In this paper, we first propose a new puncturing pattern, which is easy to realize, for RC-LDPC codes. Then, we apply RC-LDPC codes to the cross-layer design scheme combing the AMC with HARQ in MIMO fading channels.

The rest of this paper is organized as follows. In Section 2, we present the system model of the cross-layer design combining the AMC and HARQ in MIMO fading channels using STBCs. How to calculate the effective signal-to-noise ratio (SNR) and channel estimations are explained in Section 3, while the principle of the cross-layer design is illustrated in Section 4. In Section 5, we introduce the construction of RC-LDPC codes. In Section 6, we apply RC-LDPC codes to AMC–ARQ systems over MIMO fading channels with STBCs and get numerical results through simulations. Finally, some conclusions are drawn in Section 7.

2. System model

The system model of an AMC–ARQ system based on RC-LDPC codes in MIMO channels using STBCs is shown in Fig. 1. Assuming that there are N_{T} transmit antennas and N_{R} receive antennas, then the diversity order is defined as $K \triangleq N_{\mathrm{T}} N_{\mathrm{R}}$. The MIMO fading channel can be expressed as a matrix $\mathbf{H} = [h_{ij}]_{i,j=1}^{N_{\mathrm{R}},N_{\mathrm{T}}}$, where h_{ij} is the channel coefficient between the jth transmit antenna and the ith receive antenna. Under the assumption of independent Rayleigh fading, the channel coefficients h_{ij} are modeled as independent and identically distributed (i.i.d.) complex circular Gaussian random variables with zero mean and unit variance. The received signal can be expressed as

$$\mathbf{Y} = \mathbf{HX} + \mathbf{V}, \qquad (1)$$

where $\mathbf{Y}$ is a $N_{\mathrm{R}} \times T$ matrix of received symbols with T representing the number of symbols per antenna, $\mathbf{X}$ is a $N_{\mathrm{T}} \times T$ matrix of transmitted symbols, and $\mathbf{V}$ is a $N_{\mathrm{R}} \times T$ noise matrix with elements modeled as i.i.d. complex circular Gaussian random variables having zero mean and unit variance.

At the physical layer, there are multiple modulation and coding schemes (MCSs) available. Coded symbols are transmitted on a frame-by-frame basis through MIMO fading channels after space–time block coding. The CSI is estimated at the receiver and then sent back through a feedback channel to the AMC controller, which chooses the appropriate MCS in the next transmission accordingly.

At the data link layer, the selective repeat ARQ protocol is adopted to control packet retransmissions. When an error is detected in a packet, a retransmission request is generated and sent back to the transmitter via a feedback channel. For simplicity, we assume that the feedback channel is error free and has zero delay.

The packet and frame structures used in this paper are similar to those as illustrated in [1]. The only difference is that no cyclic redundancy check (CRC) codes are used in our system. This is due to the fact that LDPC codes are employed here, whose strong error detection ability enables them to act as error detection codes as well. It follows that there is no need to use CRC and thereby the system overhead can be significantly reduced. The error detection ability of LDPC codes is beyond the scope of this paper. In this paper, we simply assume that the error detection capability provided by the LDPC codes is sufficient for our system.

3. Effective SNR and channel estimation

In our system model shown in Fig. 1, the STBC encoder maps $R \leqslant T$ complex modulated symbols into N_{T} orthogonal

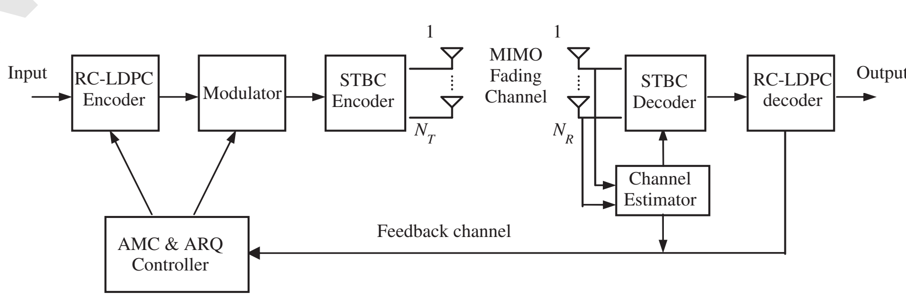

Fig. 1. System model.

complex symbol sequences of length T and then transmits them by N_{T} transmit antennas simultaneously. The coding rate of a STBC is therefore $R_c = R/T$. Let us define the average transmit power per stream/antenna as P_s. According to the effective SISO channel model for STBCs described in [7], the received symbol y before the maximum likelihood (ML) detection can be expressed as

$$y = \|\mathbf{H}\|_{\mathrm{F}}^2 s + v, \tag{2}$$

where s is the real or imaginary part of the transmitted complex symbol, v is the noise symbol with mean power σ^2 after STBC decoding, $\|\cdot\|_{\mathrm{F}}^2$ denotes the squared matrix Frobenius norm, and $\|\mathbf{H}\|_{\mathrm{F}}^2 = \sum_{i,j} h_{ij}^2$. At the receiver, the SNR is given by [8]

$$\gamma = \frac{P_s}{\sigma^2}\|\mathbf{H}\|_{\mathrm{F}}^2 = \frac{P_{\mathrm{T}}}{\sigma^2 N_{\mathrm{T}} R_c}\|\mathbf{H}\|_{\mathrm{F}}^2 = \frac{\overline{\gamma}}{N_{\mathrm{T}} R_c}\|\mathbf{H}\|_{\mathrm{F}}^2, \tag{3}$$

where P_{T} is the total transmit power transmitted on N_{T} antennas per symbol duration and $\overline{\gamma} = P_{\mathrm{T}}/\sigma^2$ is defined to be the average pseudo SNR. Since $\|\mathbf{H}\|_{\mathrm{F}}^2$ is the sum of $2K$ i.i.d. χ^2 random variables, we can get the probability density function (PDF) of γ as follows [9]:

$$p_\gamma(\gamma) = \frac{\gamma^{K-1}}{\Gamma(K)}\left(\frac{N_{\mathrm{T}} R_c}{\overline{\gamma}}\right)^K \exp\left(-\frac{N_{\mathrm{T}} R_c}{\overline{\gamma}}\gamma\right), \quad \gamma \geqslant 0, \tag{4}$$

where $\Gamma(\cdot)$ is the Gamma function.

Assuming that the receiver performs the minimum mean square error (MMSE) estimation of the channel, then $\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E}$ holds, where $\hat{\mathbf{H}}$ is the estimated channel matrix and $\mathbf{E}$ is the estimation error. We further assume that $\hat{\mathbf{H}}$ and $\mathbf{E}$ are uncorrelated. The entries of $\mathbf{E}$ are also i.i.d. zero-mean circularly symmetric complex Gaussian distributed random variables with variance $\sigma_e^2 = E(h_{ij}^2) - E(\hat{h}_{ij}^2)$. The estimated SNR $\hat{\gamma}$ has the following relationship with the instantaneous SNR γ [10]

$$\hat{\gamma} = \frac{1-\sigma_e^2}{1+\sigma_e^2 P_{\mathrm{T}}}\gamma. \tag{5}$$

Consequently, we can derive the PDF of the estimated SNR $\hat{\gamma}$ [9]

$$p_{\hat{\gamma}}(\hat{\gamma}) = \frac{\lambda^K}{\Gamma(K)}\hat{\gamma}^{K-1} e^{-\lambda\hat{\gamma}}, \quad \gamma \geqslant 0, \tag{6}$$

where $\lambda = \frac{N_{\mathrm{T}} R_c (1+\sigma_e^2 P_{\mathrm{T}})}{(1-\sigma_e^2)\overline{\gamma}}$.

The correlation between h_{ij} and its estimation $\hat{h}_{ij}$ is [9]

$$u = \frac{E(h_{ij}\hat{h}_{ij})}{\sqrt{E(h_{ij}^2)E(\hat{h}_{ij}^2)}} = \frac{1}{\sqrt{1+\sigma_e^2}}, \tag{7}$$

which indicates the quality of the channel estimation. From (5) and (7), it is clear that $\hat{\gamma} = \gamma$ and $u = 1$ hold, respectively, if $\sigma_e^2 = 0$. This is actually corresponding to the perfect channel estimation. The expression (7) further tells us that the correlation u between h_{ij} and $\hat{h}_{ij}$ is getting smaller with the increase of σ_e^2, which means that the channel estimation is becoming more inaccurate and will cause severe degradation of the system performance.

4. Cross-layer design in MIMO channels

The cross-layer design considered in this paper involves two layers, i.e., the physical layer and the data link layer. At the data link layer, the N_{r} truncated ARQ protocol is adopted. Packets received incorrectly after N_{r} retransmissions will be dropped, thus inducing packet loss. In order to meet the system delay constraint, for a given packet loss probability $\mathrm{PER}_{\mathrm{link}}$ at the data link layer, the packet error rate (PER) P_{target} at the physical layer should be [1]

$$P_{\mathrm{target}} = \mathrm{PER}_{\mathrm{link}}^{1/(N_{\mathrm{r}}+1)}. \tag{8}$$

Since the AMC is implemented at the physical layer according to the target PER, it is clear that P_{target} is the cross-layer information.

Suppose that there are N MCSs at the physical layer with increasing rates R_n $(n=1, 2, \ldots, N)$ in terms of information bits per symbol. We will consider the modulation method with the MQAM signal constellation, where M denotes the number of points in each signal constellation. If the coding rate of a MCS is R_L, we have $R_n = R_L(\log_2 M)$. As in [1], we assume constant power transmission and adopt the equivalent SISO channel model to describe the estimated instantaneous channel SNR $\hat{\gamma}$. The whole SNR range is divided into N intervals based on N thresholds γ_n, $n = 1, 2, \ldots, N$. When $\gamma_n \leqslant \hat{\gamma} < \gamma_{n+1}$, MCS n with the rate R_n will be chosen for the next transmission. Our first task is to determine the thresholds γ_n.

For a fixed MCS, the relationship between the PER and $\hat{\gamma}$ can be expressed as

$$\mathrm{PER}_n(\hat{\gamma}) = \begin{cases} 1 & \text{if } 0 < \hat{\gamma} < \gamma_{\mathrm{cf}} \\ f(\hat{\gamma}) & \text{if } \hat{\gamma} \geqslant \gamma_{\mathrm{cf}}, \end{cases}, \tag{9}$$

where n is the MCS index, γ_{cf} is the SNR cut-off value indicating that no information will be transmitted when the instantaneous SNR falls below it, $f(\cdot)$ is a function obtained by a curving fitting technique according to the exact PER curve through Monte Carlo simulations. For instance, when convolutional codes act as forward error control (FEC) codes [1]

$$f(\hat{\gamma}) = a_n \exp(-g_n\hat{\gamma}), \tag{10}$$

where a_n and g_n are parameters dependent on mode n. We will demonstrate in the following section that the function $f(\cdot)$ is different if we use LDPC codes as FEC codes. For a given target PER P_{target}, the thresholds can be obtained by inverting the PER expression in (9), i.e.,

$$\gamma_n = f^{-1}(P_{\mathrm{target}}), \quad n = 1, 2, \ldots, N. \tag{11}$$

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According to the AMC rule, each MCS n will be chosen with the following probability [1]

$$p_n = \int_{\gamma_n}^{\gamma_{n+1}} p_{\widehat{\gamma}}(\widehat{\gamma})\,\mathrm{d}\widehat{\gamma} = \frac{\Gamma(K, \lambda\gamma_n) - \Gamma(K, \lambda\gamma_{n+1})}{\Gamma(K)}. \qquad (12)$$

It can be shown that the average PER for MCS n is given by [1]

$$\overline{\mathrm{PER}}_n = \int_{\gamma_n}^{\gamma_{n+1}} \mathrm{PER}_n(\hat{\gamma})\, p_{\hat{\gamma}}(\hat{\gamma})\,\mathrm{d}\hat{\gamma}. \qquad (13)$$

Then, the total average PER can be written as follows [1]:

$$\overline{P} = \frac{\sum_{n=1}^{N} R_n \overline{\mathrm{PER}}_n}{\sum_{n=1}^{N} R_n p_n}. \qquad (14)$$

For the ARQ with N_r retransmissions, the average number of transmissions per packet can be expressed in terms of the total average PER and N_r [1]

$$\overline{N} = \frac{1 - \overline{P}^{N_\mathrm{r}+1}}{1 - \overline{P}}. \qquad (15)$$

Consequently, the average spectral efficiency of the whole system is given by [1]

$$\overline{S}_e = \frac{\sum_{n=1}^{N} R_n p_n}{\overline{N}}. \qquad (16)$$

5. RC-LDPC codes

LDPC codes are block codes that exhibit near Shannon limit performance. They were first introduced by Gallager in his thesis in 1960s [4] and rediscovered by Mackay [11] after the debut of Turbo codes. RC-LDPC codes are a family of nested codes with wide range code rates generated by a low-rate LDPC code, which is the so-called mother code. A lot of work has been done to find the optimum puncturing and extending pattern [6], but random puncturing has been adopted in most applications [5]. The problem of random puncturing is that the receiver cannot get the puncturing pattern easily. Therefore, it is difficult to put random puncturing into practice. Here, we proposed a simple puncturing method that is easy to implement and can get as good performance as random puncturing.

We construct the mother code by using the progressive edge growth (PEG) method, which has been proven to be able to produce the best LDPC codes with moderate code length and can generate a weight-increasing parity-check (WIPC) matrix [12]. We employ LDPC codes with rate 1/2 (1008, 504) in our simulations.

The variable node degree distribution of irregular LDPC codes is as follows:

$$\begin{aligned}\lambda(x) &= \sum_i \lambda_i x^i \\ &= 0.47532x^2 + 0.27953x^3 + 0.03486x^4 \\ &\quad + 0.10889x^5 + 0.10138x^{15}. \end{aligned} \qquad (17)$$

Then, the bits with degree 2 are all located in the right of the parity check matrix, corresponding to the parity check bits. When constructing RC-LDPC codes, puncturing those bits with lower degree can have less impact on the configuration of the mother code. So, for a given rate, we implement a continuous puncturing from those bits with the lowest degree.

Fig. 2 gives the bit error rate (BER) performance comparison of RC-LDPC codes with different coding rates generated by the proposed continuous puncturing and random puncturing. It is clear that compared with random puncturing, the proposed continuous puncturing results in similar or even better performance of RC-LDPC codes. But it is

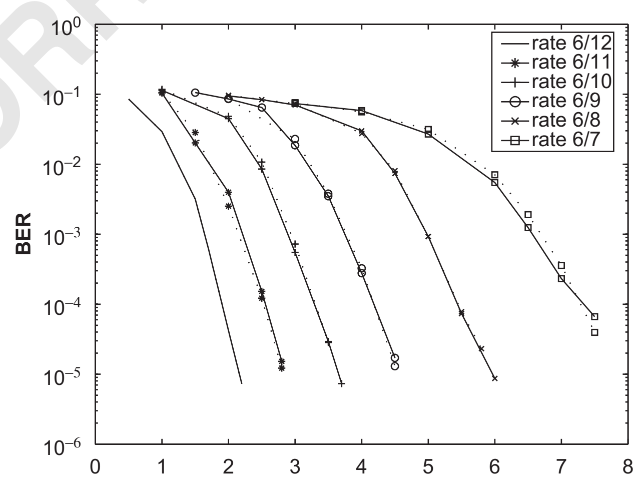

Fig. 2. BER performance comparison of RC-LDPC codes with the continuous puncturing and random puncturing (solid line: continuous puncturing; dashed line: random puncturing).

Table 1. Parameters of MCSs at the physical layer

	MCS1	MCS2	MCS3	MCS4	MCS5	MCS6
Modulation	BPSK	QPSK	QPSK	16 QAM	16 QAM	64 QAM
Coding rate	1/2	1/2	3/4	9/16	3/4	3/4
R_n (bits/sym)	0.50	1.00	1.50	2.25	3.00	4.50
a_n	2.0711	2.4654	1.3988	1.5948	1.2032	1.2086
b_n	−1.9453	1.1845	4.3105	7.2495	10.334	15.551
c_n	3.9263	3.0263	2.9004	3.4256	3.0533	2.6082
γ_{cf} (dB)	−3.3017	−0.63305	2.61	5.7713	8.7682	13.716

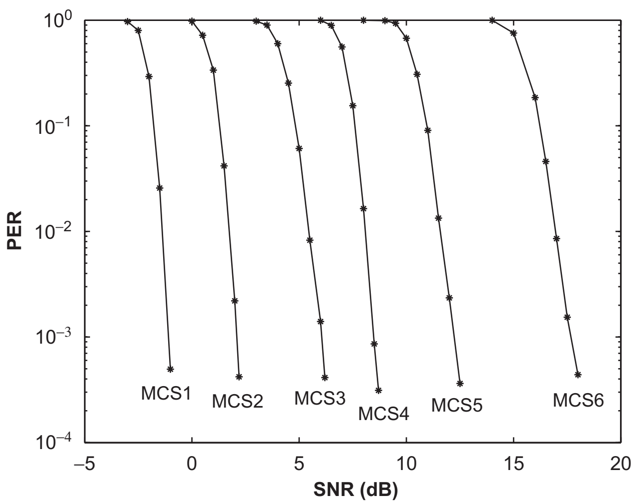

Fig. 3. PER simulation performance and fitting curves of six MCSs (star: simulation; solid line: fitting curve).

advantageous to use continuous puncturing with respect to the implementation of the system hardware. In the AMC–ARQ system, RC-LDPC codes constructed by continuous puncturing are employed. For LDPC codes, the relationship between the PER and $\hat{\gamma}$ is given by [13]

$$\mathrm{PER}_n(\hat{\gamma}) = \begin{cases} 1 & \text{if } 0 < \hat{\gamma} < \gamma_{\mathrm{cf}} \\ \left(\dfrac{1}{1+\exp\{c_n(\hat{\gamma}-b_n)\}}\right)^{a_n} & \text{if } \hat{\gamma} \geqslant \gamma_{\mathrm{cf}} \end{cases}, \tag{18}$$

where a_n, b_n, c_n and γ_{cf} are parameters obtained by fitting (18) to the simulation results. Considering the LDPC-coded modulation schemes listed in Table 1, Fig. 3 impressively shows the excellent accordance between the theoretical approximation (18) and the exact PER.

If we employ LDPC codes in the cross-layer design mentioned in Section 4, the thresholds can be obtained from (11) and (18) as follows:

$$\gamma_n = \frac{\ln\{(1/P_{\mathrm{target}})^{1/a_n} - 1\}}{c_n} + b_n, \quad n = 1, 2, \ldots, N,$$
$$\gamma_{N+1} = +\infty. \tag{19}$$

6. Numerical results

In this section, numerical results showing the effects of different parameters on the spectral efficiency of our cross-layer design framework are provided. At the physical layer, the MCSs were chosen from Table 1, where the modulation schemes and coding rates are adopted from the IEEE 802.11a standard [14]. Here, we use RC-LDPC codes instead of convolutional codes. Rate 3/4 and rate 9/16 LDPC codes were obtained from the rate 1/2 mother code through continuous puncturing.

Assume that the performance constraint at the data link layer is $\mathrm{PER}_{\mathrm{link}} = 0.01$. Let us consider three values for the maximum numbers of retransmissions, i.e., $N_{\mathrm{r}} = 0, 1, 2$. We can get the value of P_{target} from (8). Then, the thresholds can be obtained from (19) and the results are shown in Table 2 . When $\hat{\gamma} < \gamma_1$, which means that the channel is in deep fading and no payload bits will be sent.

In Fig. 4, the average spectral efficiency of the AMC–ARQ system based on RC-LDPC codes is plotted as a function of the average SNR for different values of N_{r} varying from 0 to 2, assuming the perfect channel estimation. Curves in Fig. 4(b) denote the average spectral efficiency of the system equipped with two transmit antennas and two receive antennas. For comparison purposes, in Fig. 4(a) we have also plotted the performance curves for the SISO system without the STBC. The average spectral efficiency gain offered by a MIMO system over a SISO system can be remarkable. By comparing Figs. 4(a) and (b), we conclude that compared with the SISO scenario, the MIMO system employing the STBC with 2 transmit antennas and 2 receive antennas can provide at least additional 0.5 bits/symbol spectral efficiency gain for the same average SNR and an additional 4 dB diversity gain for the same spectral efficiency. For both SISO and MIMO scenarios, the spectral efficiency improves with the increasing N_{r}. The spectral efficiency gain of the AMC–ARQ system with only one retransmission ($N_{\mathrm{r}} = 1$) exceeds that of the AMC-only system ($N_{\mathrm{r}} = 0$) by about 0.15 bits/symbol. However, the improvement degrades quickly with the increasing N_{r}, which implies that the maximum number of retransmissions need not to be very large. A small number of retransmissions can achieve sufficient spectral efficiency gain. If we use longer LDPC codes in the AMC-ARQ sys-

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Table 2. Thresholds γ_n (dB) for $N_r = 0, 1, 2$

N_r	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_6
0	−1.4082	1.7463	5.4325	8.0757	11.58	17.003	∞
1	−1.7638	1.3282	4.8042	7.5924	10.908	16.22	∞
2	−1.9214	1.1361	4.5489	7.39	10.645	15.912	∞

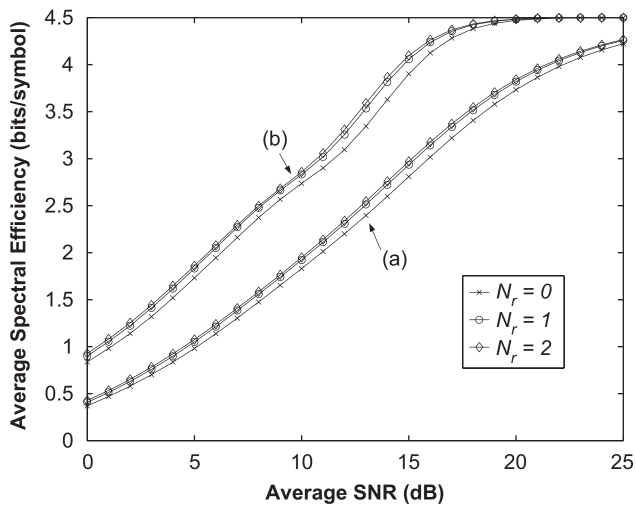

Fig. 4. Average spectral efficiency versus the average SNR for different retransmission numbers with the perfect channel estimation (a) $N_T = 1$, $N_R = 1$ (b) $N_T = 2$, $N_R = 2$.

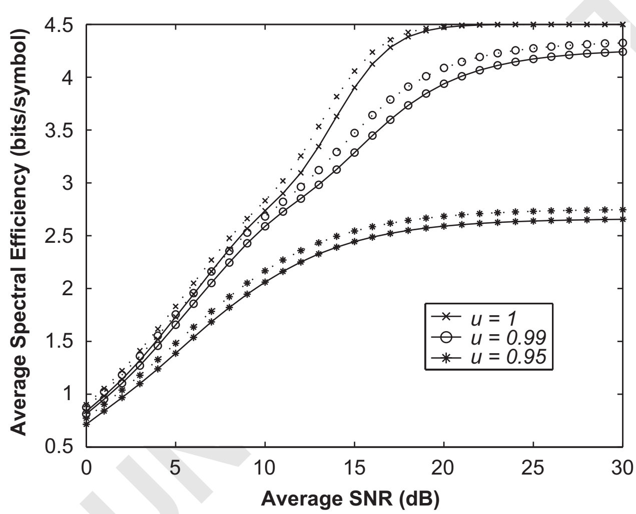

Fig. 5. Average spectral efficiency versus the average SNR for different u (dashed line: $N_r = 1$; solid line: $N_r = 0$; $N_T = 2$, $N_R = 2$).

tem, the performance for the individual MCS will be better and we can get more spectral efficiency gain.

Fig. 5 illustrates the average spectral efficiency of the system considering different channel estimation qualities. It is apparent that the largest average spectral efficiency can be achieved with the perfect channel estimation, i.e., $u = 1$. With the decrease of u, the average spectral efficiency is getting smaller. As we have mentioned previously, the performance of the whole system depends to a large extent on the accuracy of the channel estimation.

7. Conclusions

In this paper, we have proposed a continuous puncturing pattern for constructing RC-LDPC codes. The basic idea behind the continuous puncturing is that puncturing bits from the lowest degree will have the least impact on the mother code. Compared to the random puncturing, the proposed continuous puncturing is easier to implement and can generate similarly good RC-LDPC codes. We have applied RC-LDPC codes to the cross-layer design combining the AMC at the physical layer and the ARQ at the data link layer under MIMO fading channels using the STBC. The relevant MCS is chosen based on the SNR thresholds calculated according to the LDPC PER-SNR relationship. Furthermore, the impacts of the inaccurate channel estimation on the system spectral efficiency have also been investigated. Numerical results show that our AMC–ARQ system based on RC-LDPC codes can provide better spectral efficiency than the AMC-only system. More spectral efficiency gain can be obtained when longer LDPC codes are used.

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