Use of Delayed Channel Estimation Results in Adaptive Modulation

Xiao-hong SHAN(单晓红), Feng-ying WANG(王凤英), Yin-jing GUO(郭银景), Jin LI(李 瑾)
(*College of Information and Electrical Engineering, Shandong University of Science and Technology, Qingdao* 266510, *China*)

Abstract – In this paper, potential use of perfect but delayed channel estimates for variable-power discrete-rate adaptive modulation is explored. Research is concentrated on block by block adaptation. At first, a new quantity-TAUD(Tolerable Average Use Delay) is defined, it quantifies the performance of an adaptation scheme in tolerating the delay of channel estimates. Then, the research on TAUD shows that the delay tolerating performance declines with the increase in average power, the scheme working with more modulation modes can tolerate a longer delay, and such improvement will be more significant with the increase of average power. Finally, it shows that, as the delay tolerating performance determines the maximum block length, it has a great effect on the maximum spectral efficiency. The criterion for determining the block length appropriate for the target BER is described and a simple method of calculating the maximum block length is presented.

Key words – *delayed channel estimates*; *adaptive modulation*; *block by block adaptation*; *BER*; *maximum block length*; *spectral efficiency*

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1 Introduction

In recent years, to deal with the ever growing demand for wireless services with limited spectrum resources, many new transmission techniques have been developed, including adaptive transmission techniques. The basic idea behind adaptive transmission is to adapt the signaling parameters to the varying channel conditions[1-4]. It makes more efficient use of the channel capacity without sacrificing the error rate performance.

Adaptive transmission has attracted a lot of attention[5-7]. Ref. [1] and Ref. [8] show that the optimal strategy is variable-power variable-rate transmission. At the same time, they also find that when the rate is continuously varied, the extra spectral efficiency achieved by the variable-power variable-rate scheme over the constant-power counterpart is negligible. However, in practice, the rates are discrete, so power control is needed to fill the "gap" between the performances of discrete rates.

Good performances depend on accurate and timely Channel State Information (CSI) at the transmitter. However, because of its time-varying nature, the channel at the time of transmission is different than it was at the time of channel estimation. Outdated channel estimates will lead to performance deterioration. Consequently, a lot of efforts have been made to tackle this problem. Ref. [9] presents a robust adaptive signaling scheme. Ref. [10] ~[12] propose different channel prediction methods. Although they have been proved to be effective, their complexity is greatly related to that of the schemes simply using the outdated channel estimates. Furthermore, prediction errors will also lead to performance degradation. Thus, it is worth while discussing in-depth the effects of outdated CSI on the performance and tapping its potential use for adaptive transmission.

The effects of outdated CSI on BER have been studied in Ref. [1] and Ref. [4]. In this work, the block by block adaptation is concentrate on, which is more practical than the symbol by symbol adaptation. The delay tolerating performance vs. the average power for different schemes is investigated, the impact of such performance on the spectral efficiency is studied and the design criterion for the block by block adaptive system using outdated CSI is made.

2 Channel model and adaptation scheme

2.1 Channel model

The channel model is flat fading and time-discrete, sampled at the symbol rate $1/T_s$.

$$x_i = a_i + n_i. \tag{1}$$

In Eq. (1), the channel gain a_i is Rayleigh distributed.

2.2 Block by block adaptation

The structure of an adaptation block is illustrated in Fig. 1. Let T_s denote the symbol duration. The

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Corresponding author: Xiao-hong SHAN (xiaoshanhong@163.com)

block is made up of L symbol periods and $L \geqslant 2$. Not all of the L periods are spent in transmitting data symbols. One of them is reserved for transmitting (FDD) or receiving (TDD) the known information used for estimating the fading level and this T_s is named channel estimation T_s (CET_s). Assume that the channel gain at the CET_s, a_{CET_s}, is perfectly estimated. The working mode for block $j+1$ is selected based on the a_{CETs} of block j. The interval between the CET_s of block j and the head of block $j+1$ is called Initial Use Delay (IUD), whose length in T_s is τ_0 and $1 \leqslant \tau_0 \leqslant L-1$. Then for the k-th ($k=1,2,\cdots,L$) symbol in a block, the delay of the channel estimate is $(\tau_0 + k)T_s$. IUD is an inherent and unavoidable parameter of the system and dependent on the channel estimation delay. The switching speed of the transmitter from one working mode to another, and, for the FDD system, the feedback delay.

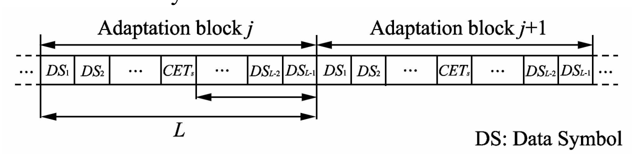

Fig. 1 Structure of adaptation block

2.3 Adaptation scheme

The variable-power discrete-rate adaptive modulation policy in this paper is derived from that in Ref. [1]. There are five candidate modulation modes: 0-QAM, BPSK, 4-QAM, 16-QAM and 64-QAM. Accordingly, the overall range of the channel gain is divided into five regions. The m-th region ($m=1,2,\cdots,5$) is denoted by $[A_{m-1}, A_m]$, where $A_0 = 0$ and $A_5 = +\infty$. r_m represents the link spectral efficiency when the a_{CET_s} falls in the m-th region. P_m represents the probability when the a_{CET_s} falls in the m-th region. Then the average spectral efficiency R (bps/Hz) is given by

$$R = \sum_{m-1}^{5} r_m P_m . \qquad (2)$$

The switching levels $A_{m's}$ are calculated according to the optimal switching scheme presented in Ref. [13]. The transmit power is subject to an average constraint.

The adaptation scheme using five modulation modes is referred to as five-rate scheme and that using just 0-QAM, BPSK, 4-QAM and 16-QAM are referred to as four-rate scheme.

3 Delay tolerating performance

In this paper, perfect AGC is assumed at the receiver and only the BER resulting from outdated channel estimates is taken into consideration.

3.1 Tolerable average use delay

It is easy to see that when L is fixed, the average BER will degrade with the increase of τ_0 and in the same way, when τ_0 is fixed, it will degrade with the increase of L. Average use delay (AUD) is defined as the average of the delays of the channel estimates for the $L-1$ data symbols in a block and it is given by

$$\bar{\tau} = [\tau_0 + (L+1)/2] + [\tau_0/(L-1) - 0.5]. \qquad (3)$$

It can be easily deduced that $\bar{\tau}$ will increase with the increase in L. Then it is safe to say that when τ_0 or L is fixed, a larger $\bar{\tau}$ will result in a higher BER.

Tolerable Average Use Delay (TAUD) is defined as the maximum AUD that results in an acceptable BER for a given target and it serves to indicate the performance of an adaptation scheme in tolerating the delay of the channel estimation results. In this paper, BERs that are less than 1.1×10^{-3} are accepted for the target BER 10^{-3}. The simulation results show that the TAUD is a constant which is dependent on the number of candidate modes, average power constraint P_a and Doppler frequency F_d. Let $\bar{\tau}_t$ denote the TAUD in T_s, then any $\bar{\tau} \leqslant \bar{\tau}_t$ will lead to a satisfactory BER and $\bar{\tau} > \bar{\tau}_t$, an unacceptable one, regardless of the L and τ_0.

The "normalized TAUD $\bar{\tau}T_sF_d$ vs. the average "SNR" for the five- and four-rate schemes is shown in Fig. 2, when the target BER is 10^{-3}.

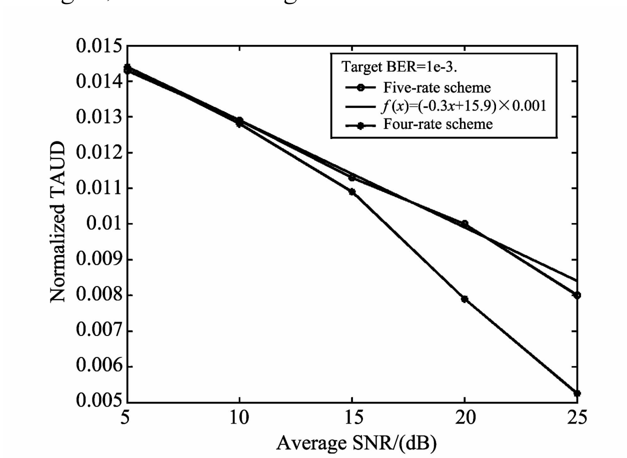

Fig. 2 Normalized TAUD vs. average SNR when the target BER = 10^{-3}

We have the observations as follows: ① The five-rate curve is approximated by the function $f(x) = (-0.3x + 15.9) \times 0.001$; ② The delay tolerating performance declines with the increasing average SNR; ③ The five-rate scheme is able to tolerate a longer delay than the four-rate one, and the difference between them expands for greater average SNR values. When the average SNR gets higher, the probability will increase that higher level modulation modes are selected. However, it can be known from intuition that higher level modulation modes are inferior to lower level ones in tolerating the delay. So, the delay tolerating performance declines, when the average SNR increases. For the same average SNR, the five-rate scheme chooses the lower level modes with larger probabilities than the four-rate one does. In consequence, it shows a better delay tolerating performance.

3.2 Average BER

With an IUD τ_0 and a block length L, for the k-th symbol in a block, the normalized delay of the channel estimate is $(\tau_0 + k)T_sF_d$ and the average BER is expressed as

$$\overline{BER}((\tau_0 + k)T_sF_d) = \frac{\sum_{m=1}^{N} r_m \overline{BER}_m((\tau_0 + k)T_sF_d)}{\sum_{m=1}^{N} P_m r_m}, \tag{4}$$

where N is the number of modulation modes, $\overline{BER}_m((\tau_0 + k)T_sF_d)$ is the average BER for the k-th symbol when the channel estimate falls in the m-th region and is given by

$$\overline{BER}_m((\tau_0 + k)T_sF_d) = \int_{A_{m-1}}^{A_m}\int_0^{\infty} BER(2^{r_m}, snr_m c_k) P_{c_k|a_{CET_s}})dc_k p_{a_{CET_s}}(a_{CET_s})da_{CET_s}, \tag{5}$$

where snr_m represents the received SNR that is required for the target BER by the modulation mode used in the m-th region, $c_k = a_k^2/a_{CET_s}^2$, a_k denotes the channel gain at the k-th symbol period in the block $j+1$, the estimate of a_k and a_{CET_s} is of the block j, $p_{a_{CET_s}}(a_{CET_s})$ is the PDF of a_{CET_s} and $p_{c_k|a_{CET_s}}$ $(c_k \mid a_{CET_s}$ is the conditional PDF of c_k with a_{CET_s} known. According to Ref. [4], it can be expressed as

$$p_{c_k|a_{CET_s}}(c_k \mid a_{CET_s}) = \frac{a_{CET_s}^2}{1-\rho_K} I_0\left[\frac{2\sqrt{\rho_k c_k}\, a_{CET_s}^2}{1-\rho_k}\right]\exp\left[-\frac{a_{CET_s}^2(c_k + \rho_k)}{1-\rho_k}\right], \tag{6}$$

where $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind, ρ_k is the correlation factor between the a_{CET_s} and the a_k. $BER(2^{r_m}, snr_m c_k)$ in Eq. (5) is the instantaneous BER for the k-th symbol when the a_{CET_s} falls in the m-th region.

The average BER for the block by block adaptive system, $< BER >_{(\tau_0, L)}$, is given as

$$< BER >_{(\tau_0, L)} = \frac{1}{L-1}\sum_{k=1}^{L}\sum_{k \neq L-\tau_0} \overline{BER}((\tau_0 + k)T_sF_d). \tag{7}$$

4 Use of TAUD in system design

4.1 Maximum block length

As the TAUD is a constant, iu can be used as a design criterion for the block by block adaptive system. With τ_0 having been determined, $\bar{\tau}_1$ is used to calculate the maximum block length, $L_{\max}(\tau_0, \bar{\tau}_t)$, available for the target BER

$$L_{\max}(\tau_1, \bar{\tau}_t) = \text{the maximum } L \text{ that satisfies } L \geqslant \tau_0 + 1 \text{ and } \bar{\tau}(\tau_0, L) \leqslant \bar{\tau}_t. \tag{8}$$

The definition in Eq. (8) implies that for an adaptive system whose operating speed is not high and delay tolerating performance is not good, that is to say, when its τ_0 is large while its $\bar{\tau}_t$ is small, it will not probably be able to find a satisfactory L.

Eq. (3) shows that to find the $L_{\max}(\tau_0, \bar{\tau}_t)$, a quadratic inequality has to be solved. Here a simple solution is given, supposing that $2\bar{\tau}_t$ is an integer.

1) By taking an average over the delay parameters of all the L symbols in a block, $\bar{\tau}'$ is obtained.

$$\bar{\tau}' = \tau_0 + (L+1)/2. \tag{9}$$

2) $L'_{\max}(\tau_0, \bar{\tau}_t)$ denotes the maximum L that satisfies $\bar{\tau}'(\tau_0, L) \leqslant \bar{\tau}_t$, then

$$L'_{\max}(\tau_0, \bar{\tau}_t) = 2 \times (\bar{\tau}_t - \tau_0) - 1. \tag{10}$$

3) It can be proved that

$$L_{\max}(\tau_0, \bar{\tau}_t) = \begin{cases} L'_{\max}(\tau_0, \bar{\tau}_t), & \tau_0 \leqslant \dfrac{L'_{\max}(\tau_0, \bar{\tau}_t) - 1}{2}; \\ L'_{\max}(\tau_0, \bar{\tau}_t) - 1, & \dfrac{L'_{\max}(\tau_0, \bar{\tau}_t), -1}{2} < \tau_0 < L'_{\max}(\tau_0, \bar{\tau}_t) - 1; \\ \text{no eligible } L, & \tau_0 \geqslant L'_{\max}(\tau_0, \bar{\tau}_t) - 1. \end{cases} \tag{11}$$

4.2 Maximum effective spectral efficiency

The distribution of the channel gain is independent of time, so the time delay of channel estimates has no effects on the average spectral efficiency. As $L-1$ of the L symbol periods is used for data, the effective spectral efficiency is given as

$$R' = R(L-1)/L. \tag{12}$$

By maximizing L, the rate of system reconfiguration can be minimized, the effective spectral efficiency is maximized.

$$R'_{max} = R(L_{max} - 1)/L_{max}. \quad (13)$$

where R'_{max} is related to the delay tolerating performance and R. Fig. 3 is presented as an illustrative example and from the figure, it can be seen that:

1) For both the five- and four-rate schemes, the 25 dB curves decrease more quickly than their 15 dB counterparts. This is because $\bar{\tau}_t$ decreases with the increase of average SNR and the L_{max} under 25 dB is less than that under 15 dB.

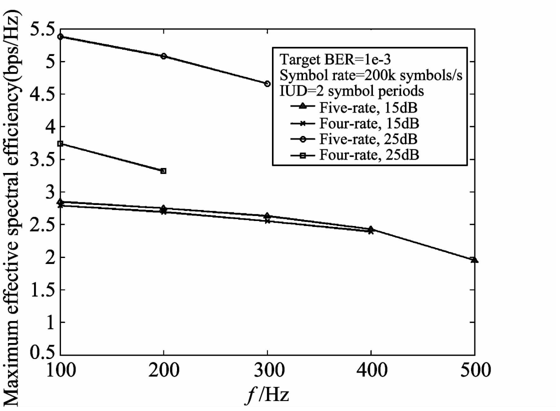

Fig.3 R'_{max} vs. F_d for five-rate schemes when the average SNR = 15 and 25dB

2) While the L_{max} is less under 25 dB average SNR, the R is greater than it is under 15 dB. In consequence, the R'_{max} is greater under 25 dB than it is under 15 dB.

3) With the average SNR being 15 dB, when F_d rises to 500 Hz, the four-rate scheme cannot find a satisfactory L, while the five-rate one can still work. With the average SNR being 25 dB, when F_d rises to just 300 Hz, the same thing happens. To work under fast fading conditions, the system must improve its delay tolerating performance. It can do this by adopting the five-rate scheme or reducing the average power.

5 Conclusions

This paper explores the potential use of perfect but outdated channel estimates for block by block adaptive MQAM.

The delay tolerating performance declines with the increase in average SNR, the five-rate system is able to tolerate a longer delay than the four-rate one, and the difference between them becomes significant for great average SNR values.

As the TAUD is a constant, it can be used as a design criterion for the adaptive system. A method of calculating the maximum block length is presented as a function of τ_0 and $\bar{\tau}_t$. To obtain a proper effective spectral efficiency, the system must have a good enough delay tolerating performance.

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