Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Adaptive modulation MIMO system based on minimizing transmission power*

WANG Zhi-ying†, HE Chen
(*Department of Electronics Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*)
†E-mail: pumawzy@hotmail.com
Received June 22, 2005; revision accepted Jan. 4, 2006

Abstract: Adaptive modulation (AM) is an effective technique to approach the theoretical bound of multi-input and multi-output (MIMO) channel. In most previous studies, the AM parameters were obtained by maximizing the transmission rate for a given total transmit power. In this paper, a novel AM-MIMO algorithm is presented, which is based on minimizing total transmit power when the link's QoS requirements are given. By taking the QoS requirements into account directly, the proposed algorithm not only makes the system more flexible, but also makes the cross layer design of wireless network easier. At last, the numerical results of the proposed scheme are presented.

Key words: MIMO system, Adaptive modulation (AM), QoS
doi:10.1631/jzus.2006.A1046 **Document code:** A **CLC number:** TN919.72

INTRODUCTION

Many adaptive modulation (AM) schemes have been proposed for multi-input and multi-output (MIMO) and its derivations to increase the data throughput (June and Rao, 2002; Zhou and Vucetic, 2004a; 2004b; Chen *et al*., 2004; Zhou and Giannakis, 2004b). By using some kinds of greedy algorithms, all of these AM schemes try to maximize the transmission rate for a given transmission power. Their performances under different conditions have been studied deeply. The AM-MIMO with perfect channel state information (CSI) feedback is discussed in (June and Rao, 2002; Zhou and Vucetic, 2004a; Chen *et al*., 2004). And as complementarities, the partial and inaccurate CSI feedback was studied in (Zhou and Giannakis, 2004b; Zhou and Vucetic, 2004b). Furthermore, the influences of feedback precision were studied in (Zhou and Giannakis, 2004a).

When the link's QoS requirements, especially the transmission rate and bit error rate (BER) are decided by the supported service type, the existing AM-MIMO (June and Rao, 2002; Zhou and Vucetic, 2004a; 2004b; Chen *et al*., 2004; Zhou and Giannakis, 2004a; 2004b) based on certain power budget may lead to waste of transmission power or poorer performance. Therefore, the AM scheme based on minimized transmit power which can meet the link's QoS requirements may be more preferred under this condition. It not only makes the system more flexible, but also makes the cross layer optimization easier by taking the QoS parameters into account when designing the physical layer.

Based on the advantages stated above, we propose a novel AM-MIMO system in this paper, which aims at minimizing the total transmit power when QoS parameters are given. For simplicity, only two basal parameters of QoS—transmission rate and BER—are taken into consideration in this study.

AM-MIMO SYSTEM MODEL

We assume a flat fading MIMO channel with N_t

* Project (Nos. 60272082 and 60372076) supported by the National Natural Science Foundation of China

transmit and N_r receive antennas, which is represented by a matrix $\boldsymbol{H} \in \mathbb{C}^{N_r \times N_t}$. Its input, output and additive white Gaussian noise (AWGN) are denoted by vectors $\boldsymbol{x} \in \mathbb{C}^{N_t \times 1}$, $\boldsymbol{y} \in \mathbb{C}^{N_r \times 1}$ and $\boldsymbol{n} \in \mathbb{C}^{N_r \times 1}$, respectively. The elements of $\boldsymbol{n}$ are assumed to be independent complex Gaussian variables with zero mean and variance σ^2. Then the system can be written as:

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}. \tag{1}$$

When the channel matrix $\boldsymbol{H}$ is perfectly available at both the transmitter and the receiver, the MIMO channel can be decomposed into k parallel single-input and single-output (SISO) sub-channels with power gain λ_i (i=1, …, k) (Zhou and Vucetic, 2004a). Here, k is the rank of $\boldsymbol{H}$, and λ_i (i=1, …, k) are the nonzero eigenvalues. All of them can be obtained by applying singular value decomposition (SVD)

$$\boldsymbol{H} = \boldsymbol{U} \cdot \mathrm{diag}(\sqrt{\lambda_1} \quad \cdots \quad \sqrt{\lambda_k}) \cdot \boldsymbol{V}^{\mathrm{H}}, \tag{2}$$

where $\boldsymbol{U} \in \mathbb{C}^{N_r \times k}$ and $\boldsymbol{V} \in \mathbb{C}^{N_t \times k}$ are matrices with left and right singular vectors of $\boldsymbol{H}$ as their columns, respectively.

Based on Eq.(2), we construct the proposed AM-MIMO system shown in Fig.1. Our aim is to determine the proper AM parameters when the required transmission rate R_{tgt} (bits/sample) and BER Ber_{tgt} are given. For practical purpose, we assume that R_{tgt} is a positive integer in this paper.

The symbols we adopt are as follows: we use b_i and Ber_i to denote the instantaneous modulation order and corresponding BER estimation for the ith sub-channel respectively; P_i and $P_{\mathrm{ttl}}=\sum_{i=1}^{k} P_i$ are the transmit power of the ith sub-channel and total transmission power, respectively.

GENERAL PROBLEM DESCRIPTION

For simplicity, we assume an uncoded MIMO using rectangular quadrature amplitude modulation (QAM). According to (Chung and Goldsmith, 2001), the BER performance of the ith sub-channel can be approximated by

$$Ber_i = 0.2\exp\left(\frac{-1.6 P_i \lambda_i}{\sigma^2 (2^{b_i} - 1)}\right). \tag{3}$$

It is accurate enough when $b_i \geq 2$. Thus, the transmission power of the ith sub-channel can be expressed as

$$P_i = \frac{-\sigma^2 (2^{b_i} - 1)\ln(5Ber_i)}{1.6\lambda_i}. \tag{4}$$

According to Eq.(4), the proposed AM-MIMO can be described by a nonlinear constrained optimization problem as follows:

$$[b_i, Ber_i]_{\mathrm{opt}} = \arg\min P_{\mathrm{ttl}}, \tag{5a}$$

$$\text{s.t.} \sum_{i=1}^{k} b_i = R_{\mathrm{tgt}},\ b_i \geq 0, \tag{5b}$$

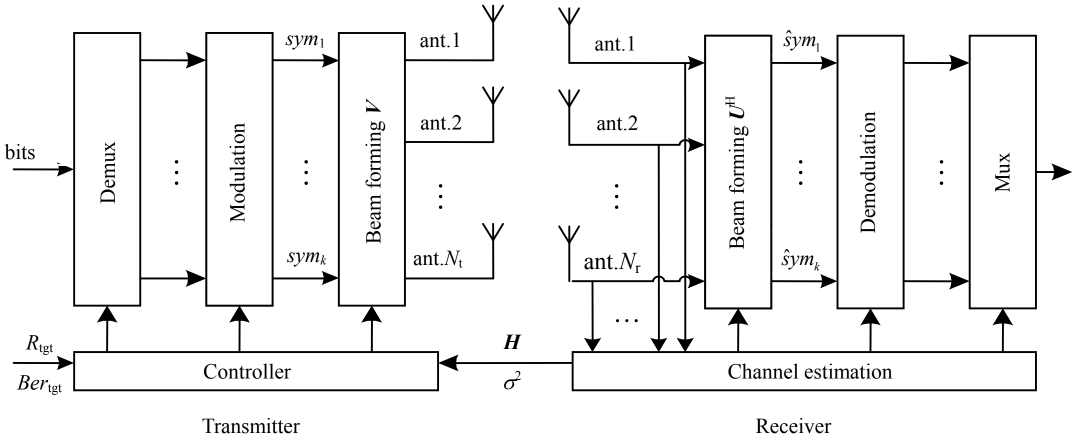

Fig.1 Adaptive feedback MIMO system based on QoS requirements

$$\frac{1}{R_{\rm tgt}}\sum_{i=1}^{k} b_i \cdot Ber_i \le Ber_{\rm tgt}. \tag{5c}$$

The optimal power allocation and modulation parameters are decided by the solution of Eq.(5). And in theory, they can make AM-MIMO system achieve expected $R_{\rm tgt}$ and $Ber_{\rm tgt}$ at the cost of minimum total transmission power.

THEORETICAL SOLUTION

Due to the complicated form of Eq.(4) and the nonlinear constraints Eqs.(5b) and (5c), the closed-form solution to the optimization problem Eq.(5) is not available. To simplify this problem, we assume an equal BER constraint to reduce the degrees of freedom,

$$Ber_i = Ber_{\rm tgt}, \tag{6}$$

and optimization problem Eq.(5) is transformed to

$$[b_i]_{\rm opt} = \arg\min \sum_{i=1}^{k} \frac{-\sigma^2 (2^{b_i}-1)\ln(5Ber_{\rm tgt})}{1.6\lambda_i}, \tag{7a}$$

$$\text{s.t.} \sum_{i=1}^{k} b_i = R_{\rm tgt},\ b_i \ge 0. \tag{7b}$$

To get the closed-form solution directly, we further assume that b_i can be any real value. Then Lagrangian method (Fletcher, 1987) can be used here, and the equation is

$$L(b_i, c) = \sum_{i=1}^{k} A_i (2^{b_i}-1) - c\left(\sum_{i=1}^{k} b_i - R_{\rm tgt}\right), \tag{8}$$

where

$$A_i = \frac{-\sigma^2 \ln(5Ber_{\rm tgt})}{1.6\lambda_i}, \tag{9}$$

and c is the Lagrangian multiplier. Thus, we can obtain the theoretical optimal modulation scheme $\{b_i\}$ by

$$c = \sqrt[k]{2^{R_{\rm tgt}} \cdot \prod_{i=1}^{k} A_i} \cdot \ln 2, \tag{10a}$$

$$b_i = \frac{1}{k}\log_2\left(2^{R_{\rm tgt}} \cdot \prod_{i=1}^{k} A_i\right) - \log_2 A_i, \tag{10b}$$

and the corresponding power allocation scheme $\{P_i\}$ by Eq.(4).

DISCRETIZATION ALGORITHM

For $\{b_i\}$, the solutions of Eq.(8) are real values, and we want to find a set of non-negative integers $\{\hat{b}_i\}$ as substitutes that minimize the distance between $\{b_i\}$ and $\{\hat{b}_i\}$. Thus, we improve the discretization algorithm originated from (Chow *et al*., 1995), which includes the following steps:

Step 1: Initialization. Round $\hat{b}_i$ to the nearest integers $\hat{b}_i = round(b_i)$, i=1, …, k; and adjust $\hat{b}_i$ into the closed range [0, $R_{\rm tgt}$], if $\hat{b}_i > R_{\rm tgt}$, then $\hat{b}_i = R_{\rm tgt}$, else if $\hat{b}_i < 0$, then $\hat{b}_i = 0$, i=1, …, k.

Step 2: If $R_{\rm tgt} > \sum_{i=1}^{k} \hat{b}_i$, then calculate the difference vector: $\boldsymbol{diff} = \hat{\boldsymbol{b}} - \boldsymbol{b}$; else go to Step 4.

Step 3: Select the sub channel with the minimal difference $j = \arg\min_i (diff_i)$, where $diff_i$ denotes the ith element of the vector $\boldsymbol{diff}$; and add one bit to this sub channel $\hat{b}_j = \hat{b}_j + 1$, at last restart Step 2 again.

Step 4: If $R_{\rm tgt} < \sum_{i=1}^{k} \hat{b}_i$, then $\boldsymbol{diff} = \boldsymbol{b} - \hat{\boldsymbol{b}}$; else go to Step 6.

Step 5: Still select the sub channel with the minimal difference $j = \arg\min_i (diff_i)$; and subtract one bit from this sub channel $\hat{b}_j = \hat{b}_j - 1$, at last restart Step 4 again.

Step 6: Finish the algorithm.

The flow chat of the proposed discretization algorithm is shown in detail in Fig.2.

After discretization, the final transmission power of the ith sub-channel is given by

$$\hat{P}_i = \frac{-\sigma^2 (2^{\hat{b}_i}-1)\ln(5Ber_{\rm tgt})}{1.6\lambda_i}, \tag{11}$$

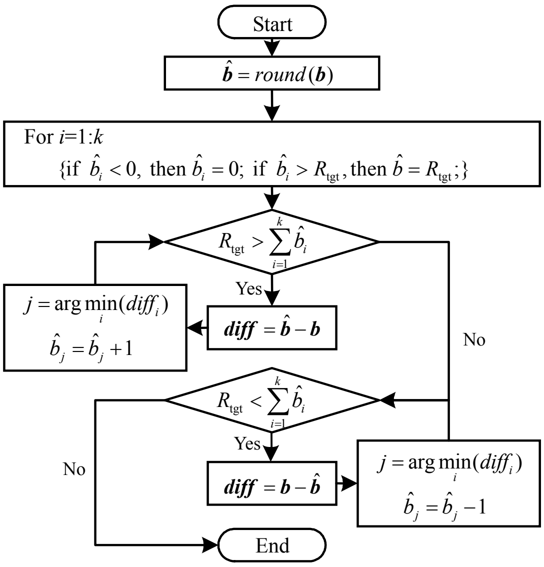

Fig.2 Flow chat of proposed discretization algorithm

and total transmit power is

$$\hat{P}_{\text{ttl}} = \sum_{i=1}^{k} \hat{P}_i. \tag{12}$$

In fact, $\hat{P}_{\text{ttl}}$ is the approximation of minimum transmission power needed to meet the link's QoS requirements (R_{tgt}, Ber_{tgt}). The performance gap between the solution of Eqs.(5) and (12) is given in Fig.3, where a 2×2 and a 4×4 uncoded MIMO system are used. From Fig.3, we can see that the influence of equal BER assumption Eq.(6) on total transmission power is very little and negligible.

NUMERICAL SIMULATIONS

For illustrative purpose, we apply the proposed algorithm (equal BER assumption) to a 2×2 and a 4×4 MIMO channel. The component modulation schemes are uncoded rectangular QAMs, and the required QoS parameters are chosen from the sets: $R_{\text{tgt}} \in \{5,10,15\}$, $Ber_{\text{tgt}} \in \{10^{-1},10^{-2},10^{-3},10^{-4}\}$. In all of these simulations, we set the AWGN power level σ^2=1.

Fig.4 shows that the real BER performances of the proposed AM-MIMO algorithm are quite close to the expected BER performance Ber_{tgt} in all of these system configurations.

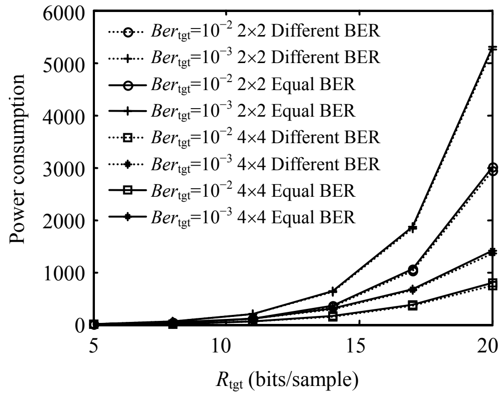

Fig.3 Influences of equal BER assumption (σ^2=1)

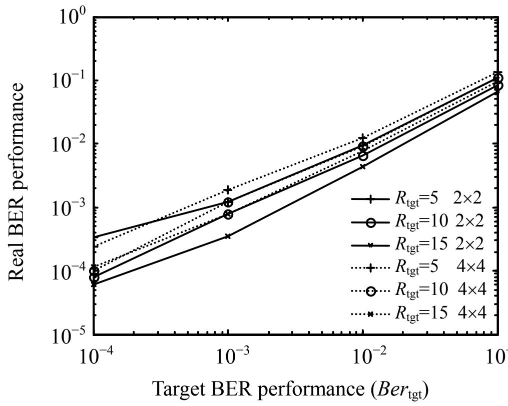

Fig.4 Real BER performances of the proposed algorithm

Fig.5 gives the total transmission power consumption of these two MIMO. As expected, when the antenna pairs increase or QoS requirements decrease, the total transmission power decreases accordingly, i.e., much transmission power is saved.

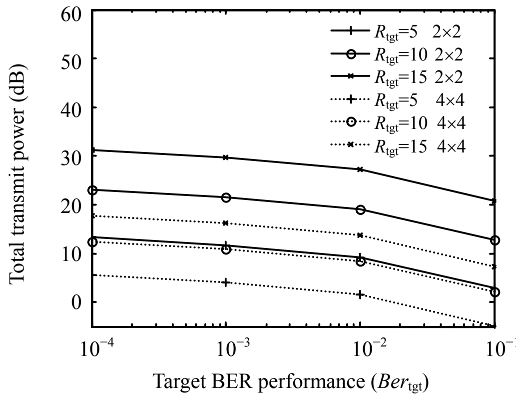

Fig.5 Total power consumption of the proposed algorithm

For further discussion, we compare the simulation result of the proposed algorithm with that of the maximal ASE (MASE) AM-MIMO system in (Zhou and Vucetic, 2004a), which is a typical AM-MIMO scheme to maximize data throughput for a given overall transmission power. In a 2×2 MIMO channel stated above, the average data transmission rate of the MASE AM-MIMO system is 7.3693 bits/sample under SNR=15 dB and $Ber_{tgt}=10^{-3}$. Compared with the proposed algorithm, some 30% bandwidth or 3 dB transmission power is not utilized sufficiently in the MASE AM-MIMO system when the target transmission rate is R_{tgt}=5 bits/sample. On the other hand, when R_{tgt} is larger, such as 10 bits/sample, the MASE AM-MIMO cannot provide sufficient bandwidth to ensure the required QoS, about 26% bits be transmitted in time. Therefore, the proposed minimized transmission power AM-MIMO is much more flexible and preferred when the multi-services are supported.

CONCLUSION

In this paper, we propose a feedback adaptive MIMO system that is optimized based on minimizing total transmit power. When the transmitter gets the perfect CSI from the receiver, the proposed algorithm could meet the link's QoS requirements at the cost of possible minimum transmission power. For simplicity and practicability, in the proposed scheme, we only take target transmit rate and target BER performance into account, which are two elementary QoS parameters. The benefits of the proposed algorithm are obvious: it not only makes the AM-MIMO more flexible, but also makes it easier to implement multi-layers combined optimization of wireless communication network by introducing the upper layer requirements into physical transceiver design.

References

Chen, X., Chai, C.C., Chew, Y.H., 2004. Constrained Power Allocation Algorithm for Rate Adaptive MIMO System. IEEE Eighth International Symposium on Spread Spectrum Techniques and Applications, p.924-928.

Chow, P.S., Cioffi, J.M., Bingham, J.A.C., 1995. A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels. *IEEE Transactions on Communications*, **43**(2):773-775. [doi:10.1109/26.380108]

Chung, S.T., Goldsmith, A.J., 2001. Degrees of freedom in adaptive modulation: a unified view. *IEEE Transactions on Communications*, **49**(9):1561-1571. [doi:10.1109/26.950343]

Fletcher, R., 1987. Practical Methods of Optimization. Wiley-Interscience, New York, p.222-230 (in Chinese).

June, C.R., Rao, B.D., 2002. Adaptive Modulation for Multiple Antenna Channels. Conference Record of the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers, **1**:526-530.

Zhou, S.L., Giannakis, G.B., 2004a. How accurate channel prediction needs to be for transmit-beamforming with adaptive modulation over Rayleigh MIMO channels? *IEEE Transactions on Wireless Communications*, **3**(4): 1285-1294. [doi:10.1109/TWC.2004.830842]

Zhou, S.L., Giannakis, G.B., 2004b. Adaptive modulation for multiantenna transmissions with channel mean feedback. *IEEE Transactions on Wireless Communications*, **3**(5): 1626-1636. [doi:10.1109/TWC.2004.833411]

Zhou, Z.D., Vucetic, B., 2004a. MIMO Systems with Adaptive Modulation. IEEE 59th Vehicular Technology Conference, **2**:765-769.

Zhou, Z.D., Vucetic, B., 2004b. Design of adaptive modulation using imperfect CSI in MIMO systems. *Electronics Letters*, **40**(17):1073-1075. [doi:10.1049/el:20045077]