Throughput Maximization by Adaptive Threshold Adjustment for AMC Systems

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***Abstract*—The mechanisms of *adaptive modulation and coding (AMC)* and *hybrid automatic repeat request (HARQ)* are two important schemes in modern wireless communication systems. In practical system design, the AMC mechanism is usually implemented with fixed switching thresholds for the modulation and coding schemes (MCS), and suffers from performance degradation. To mitigate this problem, a novel algorithm is proposed in this paper to maximize the system throughput. The algorithm adaptively adjusts the AMC threshold values according to the HARQ acknowledge (ACK) feedback information in each transmission round so that the AMC mechanism can select the best MCS with nearly optimal thresholds. Simulations are conducted to show that the system throughput is indeed improved by the proposed adaptive threshold adjustment algorithm.**

I. Introduction

In the communication systems developed in recent years, the data applications are becoming more and more important than the traditional voice service. Contrary to the voice service that has both delay and quality constraints, data applications are usually more tolerant of delay, thus allowing exploitation of the theoretical time-domain water-filling benefit. The most common water-filling approach is adaptive modulation and coding (AMC) which adjusts the transmission power, modulation and coding rate according to the instantaneous channel condition to maximize the average throughput [1]. Because of the popularity and importance of wireless data services, AMC has been a key technology, which is adopted in modern wireless systems such as 3GPP High Speed Downlink Packet Access (HSDPA) [2], cdma2000 1x Evolution for Data and Voice (1xEVDV) [3], IEEE 802.16 [4], and 3GPP Long Term Evolution (LTE) [5], in order to offer high data rate in time-varying fading channels. The AMC mechanism usually requires channel condition feedback from the receiver to the transmitter. Hence it may not perform well if the channel varies too rapidly compared to the feedback rate. This problem can be alleviated with the use of hybrid automatic repeat request (HARQ) which provides time diversity to improve transmission robustness [6]. In fact, the use of HARQ allows AMC to operate more aggressively and further boosts the system throughput [7].

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Although the HARQ mechanism can enhance the robustness of the system and hence boost system performance, it suffers from the problem of increased latency due to the round trip delay of the acknowledgement (ACK) signaling. In conventional HARQ systems, during the transmission period of each data frame, the system does not change the modulation and coding scheme (MCS) used until the frame is successfully received or the maximum number of the retransmission rounds is reached. One important reason why the latency increases is that the transmitter does not select the MCS which best fits the channel condition in retransmission rounds. Therefore, in the literature, there are a variety of works developed to handle this issue. A straightforward idea to decrease the number of retransmission rounds of HARQ, which is called *adaptive HARQ*, is to vary the MCS used in each retransmission round in order to select a best fit MCS in fast fading channel and hence the number of retransmission rounds can be minimized [8].

In addition, in practical system implementation, the thresholds of AMC mechanism for switching the MCSs are generally determined under some simplified channel assumptions and stored in the systems. If the channel statistics were fixed and the transmission system always switched the MCSs with correct thresholds, the optimal throughput could be obtained. However, in reality, the communication channel may vary with time, and the optimal thresholds will vary with the channel statistics. As a result, the pre-determined thresholds will not be optimal for switching MCSs, and there will be a great performance loss. In [9], [10], and [11], the problem was discussed and analyzed for non-adaptive HARQ with constant transmission time interval (TTI). In these studies, methods to adaptively adjust thresholds were proposed, but these methods can not be applied to adaptive HARQ.

In this paper, a novel and simple algorithm is proposed to improve the system throughput for AMC systems with adaptive HARQ.

II. System Model

In this study, the system considered includes a transmitter, a receiver, a single-input single-output (SISO) forward channel, and an error-free feedback channel between transmitter and receiver. The receiver keeps measuring the received signal-to-noise ratio (SNR), and reporting it back to the transmitter via the feedback channel with a constant feedback delay. It is

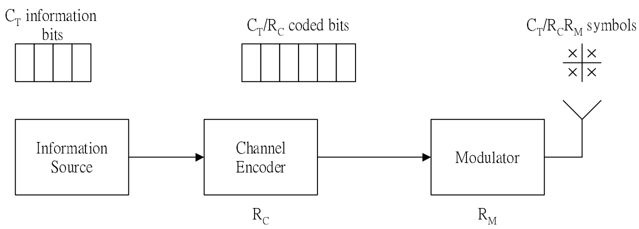

Fig. 1. Simplified transmitter block diagram.

assumed that the transmitter does not have the knowledge of the long term channel statistics and the transmission power is constant. It is also assumed that the system is equipped with both the AMC and the HARQ mechanisms.

To illustrate the transmission process, the simplified block diagram of the wireless transmitter in Fig. 1 is considered. When the transmission starts, there is a data frame of information bits with length C_T generated from the information source block and buffered to be transmitted. If the transmitter decides to transmit it with the MCS of nominal rate R, the information bit frame is firstly encoded by channel coding and rate-matching processes with coding rate R_C, and then modulated with modulation rate R_M. The relationship among the rates R, R_C, and R_M is

$$\begin{aligned} &R\ (information\ bits\ per\ symbol) \\ &\quad = R_C\ (information\ bits\ per\ coded\ bit) \\ &\quad \times R_M\ (coded\ bits\ per\ symbol). \end{aligned} \tag{1}$$

When AMC is considered, the transmitter has to select an MCS which fits the current channel condition best and can get maximum throughput. That is, the transmitter has to select an MCS $\hat{\theta}$ such that

$$\hat{\theta} = \arg\max_{\theta} \eta(\theta(\hat{\rho})), \tag{2}$$

where $\hat{\rho}$ is the instantaneous received SNR value measured and reported by the receiver, θ is the MCS index and is a function of $\hat{\rho}$, and η is the system throughput and is a function of θ.

For implementation simplicity, practical system usually keeps a pre-determined lookup table for deciding MCS. It is assumed that there is a set $\mathfrak{S}_M$ of M possible MCSs with nominal rates $R_1, R_2, \cdots, R_{\mathsf{M}}$, denoted as $\mathfrak{S}_M = \{MCS_i : i = 1, 2, \cdot, \mathsf{M}\}$, and the MCS lookup table contains a set $\mathfrak{S}_T$ of $\mathsf{M}-1$ threshold values, denoted as $\mathfrak{S}_T = \{\Gamma_i : i = 1, 2, \cdots, \mathsf{M}-1\}$. The MCS selection strategy then can be expressed as

$$\theta(\hat{\rho}) = \begin{cases} 1, & \hat{\rho} \in (-\infty, \Gamma_1); \\ m, & \hat{\rho} \in [\Gamma_{m-1}, \Gamma_m); \\ \mathsf{M}, & \hat{\rho} \in [\Gamma_{\mathsf{M}-1}, \infty). \end{cases} \tag{3}$$

When HARQ is considered, after the frame is received, the receiver decodes the frame and checks if the frame is correct by cyclic redundant check (CRC). If the frame is correctly decoded, the receiver sends an ACK signal to the transmitter to ask for next data frame. If the receiver fails to correctly decode the frame, it sends a NAK signal to the transmitter to ask for retransmission of the same coded frame (or its redundancy version) until the frame is successfully decoded or the maximum transmission limit L is reached. If the frame is still not correctly decoded after the maximum L transmissions, the receiver will claim the frame to be erroneous and ask for next data frame. For HARQ without frame combining or with Chase combining [6], the same coded frame is transmitted at each retransmission round. If frame combining is not implemented, the receiver only uses the most recent retransmission of the frame in the decoding. For Chase combining, the receiver softly combines all transmissions of the data frame and utilizes the accumulated signal in the decoding. Through frame combining, the failed transmissions of the data frame are not wasted because the receiver uses them to increase the decoding SNR. If incremental redundancy (IR) HARQ [6] is adopted in the system, the transmitter sends a different redundancy version of the coded frame in each retransmission round. After the receiver combines these redundancy versions, not only the decoding SNR is increased, the coding rate is also reduced. In summary, compared to HARQ without frame combining, Chase combining improves the system performance via accumulated SNR in decoding, while IR further enhances the performance by reducing the coding rate.

The HARQ protocol adopted in the system in this study is *adaptive HARQ*, which means that the MCS used in each retransmission round can be changed and can be different from the MCS used in the initial transmission. The receiver combines the transmissions of the frame with frame combing. For the adaptive HARQ in consideration, it is assumed that the system maintains a lookup table for deciding the MCS used in each transmission. In each transmission and retransmission, the transmitter decides which MCS is adopted by looking up the MCS lookup table only according to the instantaneous received SNR $\hat{\rho}$ measured and reported by the receiver. The target of this study is to adaptively adjust the values of the SNR thresholds $\{\Gamma_1, \Gamma_2, \cdots, \Gamma_{\mathsf{M}-1}\}$ in the MCS lookup table.

III. Proposed Algorithm

From the introduction and discussion above, the purpose of the proposed algorithm is to select an MCS which best fits the current channel condition and is able to adaptively adjust the MCS switching thresholds, so that the system throughput can always be maximized for any given channel statistics. For adaptive HARQ, it should be noted that the cases of the initial transmission round and the retransmission rounds of the data frame should be considered separately. For the initial transmission round, not only the expected throughput but also the nominal rate should be considered in the selection of the MCS. For the retransmission rounds of the frame, the nominal rate, which means the amount of information bits need to be transmitted, has been determined in the initial round, and hence the only concern is to select an MCS which can complete the transmission of the data frame as fast as possible. Therefore, the algorithm is also separated into two parts to fit the different goals of the two types of transmissions. The detail discussion is stated in the following subsections.

A. Initial Transmission Round

To analyze the problem, first of all, we define the event A_i as the event that the transmitter gets an ACK signal when MCS_i is selected in the initial transmission round. Then the average throughput η_i of the transmission when the MCS_i with nominal rate R_i is selected in the initial transmission round under the condition that the instantaneous received SNR measured (for determination of the initial MCS) being $\hat{\rho}$ can be expressed as

$$\begin{aligned}\eta_i(\hat{\rho}) &= \lim_{N_i \to \infty} \frac{R_i \times N_{A_i}(\hat{\rho})}{N_i(\hat{\rho})} \\ &= R_i \times p_{A_i}(\hat{\rho}),\end{aligned} \tag{4}$$

where N_i is the number of times MCS_i is selected in the initial transmission round, N_{A_i} is the number of times A_i occurs, and p_{A_i} is the probability the event A_i occurs and can be defined as

$$p_{A_i}(\hat{\rho}) = \lim_{N_i(\hat{\rho}) \to \infty} \frac{N_{A_i}(\hat{\rho})}{N_i(\hat{\rho})}. \tag{5}$$

Since the optimal thresholds cannot be known before the data communication takes place, the transmitter only initializes a lookup table with a pre-determined set of threshold points $\mathfrak{S}_T$. The condition for the threshold Γ_i to be optimal and maximizing the throughput is that the MCS on either side of the threshold yields the same throughput

$$\begin{aligned}&\eta_i(\Gamma_i) = R_i \times p_{A_i}(\Gamma_i) \\ =&\eta_{i+1}(\Gamma_i) = R_{i+1} \times p_{A_{i+1}}(\Gamma_i).\end{aligned} \tag{6}$$

Using the method proposed in [11], we define a threshold band i as

$$[\Gamma_i - \gamma_i^-, \Gamma_i + \gamma_i^+), \tag{7}$$

where γ_i^- and γ_i^+ define the lower and upper ranges of the threshold band, respectively.

If γ_i^- and γ_i^+ are small enough, (6) can be approximated by

$$R_i \frac{Pr(A_i^i)}{Pr(B_i^i)} \approx R_{i+1} \frac{Pr(A_{i+1}^i)}{Pr(B_{i+1}^i)}, \tag{8}$$

where the notation $Pr(X)$ means the probability of the event X, B_m^i means the event that the MCS_m is selected when the measured SNR $\hat{\rho}$ falls in threshold band i, and A_m^i means the event that the ACK signal is received when MCS_m is used in threshold band i.

To simplify (8), we force the following assumption for each threshold band:

$$Pr(A_i^i) = Pr(A_{i+1}^i), \tag{9}$$

which can be achieved by alternating the MCS selection when the measured SNR falls in a threshold band as:

- If A_i^i happens, select MCS_{i+1} the next time $\hat{\rho} \in [\Gamma_i - \gamma_i^-, \Gamma_i + \gamma_i^+)$.
- If A_{i+1}^i happens, select MCS_i the next time $\hat{\rho} \in [\Gamma_i - \gamma_i^-, \Gamma_i + \gamma_i^+)$.
- Otherwise, when $\hat{\rho} \in [\Gamma_i - \gamma_i^-, \Gamma_i + \gamma_i^+)$, the MCS is kept the same as the previous transmission.

Then we have:

$$\frac{R_i}{Pr(B_i^i)} \approx \frac{R_{i+1}}{Pr(B_{i+1}^i)}. \tag{10}$$

Note that when the SNR does not fall in any threshold band, the MCS selection is regular, i.e., selecting MCS_i when the SNR is between Γ_{i-1} and Γ_i.

Considering the problem how to adaptively adjust the thresholds, we may adjust the threshold Γ_i higher by $\delta_{B_{i+1}^i}$ when B_{i+1}^i happens. This is because, with (9), more frequent B_{i+1}^i means lower throughput of MCS_{i+1} than MCS_i at Γ_i. Thus Γ_i is lower than its optimal value. Similarly, we may adjust the threshold Γ_i lower by $\delta_{B_i^i}$ when B_i^i happens. When Γ_i is at its optimal value, the up-adjustments and down-adjustments should balance up, so Γ_i does not move on average. Therefore, we need

$$Pr(B_{i+1}^i)\delta_{B_{i+1}^i} = Pr(B_i^i)\delta_{B_i^i}. \tag{11}$$

Comparing (10) and (11), the relationship for step-size values can be derived as

$$\frac{\delta_{B_i^i}}{\delta_{B_{i+1}^i}} = \frac{R_{i+1}}{R_i}. \tag{12}$$

B. Retransmission Round

In the retransmission rounds, because the nominal rate and the number of the information bits to be transmitted were already fixed in the initial transmission round, the transmitter only needs to decide which MCS is best for transmitting the equivalent number of information bits left so that the number of the retransmission rounds can be minimized. Hence, the consideration for the selection of MCS is transformed to the condition how to arrange the resources for each remaining information bit to be effectively transmitted. In this study, it is assumed that the only indication of the available resources for MCS selection is the received SNR. Therefore, the MCS selection problem is now transformed to selecting a suitable MCS to transmit information bits according to *the SNR available for each information bit*, i.e., the normalized SNR.

To calculate normalized SNR in the retransmission round j, firstly the equivalent number of information bits left to be transmitted in this round should be measured. The information bit effectively received by the receiver in the transmission round l can be computed at the receiver as

$$C_R^l = \log_2(1 + \hat{\rho}^l), \tag{13}$$

where $\hat{\rho}^l$ is the actual received SNR at round l.

Then the estimated equivalent number of the information bits left to be transmitted at retransmission round k can again be computed at the receiver as

$$C_T^{(k)} = \tilde{R} - \sum_{l=1}^{k-1} C_R^l = \tilde{R} - \sum_{l=1}^{k-1} \log_2(1+\hat{\rho}^l), \quad (14)$$

where $\tilde{R}$ is the nominal rate in information bits per symbol (computed as in (1)) selected in the initial transmission round.

Therefore, the normalized SNR value $\tilde{\rho}_j$ the retransmission round j can provide per remaining information bit is

$$\tilde{\rho}_j = \frac{\hat{\rho}}{C_T^{(j)}}, \quad (15)$$

where $\hat{\rho}$ is the measured instantaneous SNR at round j used to derive the normalized SNR $\tilde{\rho}_j$ to be fed back to the transmitter.

To select an MCS in the retransmission round, a set of normalized threshold values $\tilde{\mathfrak{S}}_T = \{\tilde{\Gamma}_i : i = 1, 2, \cdots, \mathsf{M}-1\}$ is defined.

Then the MCS is selected according to the normalized SNR feedback instead of the instantaneous received SNR feedback used in the initial round. That is, similar to the formulation in (2), the MCS selection in retransmission round is

$$\theta(\tilde{\rho}_j) = \begin{cases} 1, & \tilde{\rho}_j \in (-\infty, \tilde{\Gamma}_1); \\ m, & \tilde{\rho}_j \in [\tilde{\Gamma}_{m-1}, \tilde{\Gamma}_m); \\ \mathsf{M}, & \tilde{\rho}_j \in [\tilde{\Gamma}_{\mathsf{M}-1}, \infty). \end{cases} \quad (16)$$

Thereafter, to adaptively adjust the thresholds in retransmission rounds, a normalized threshold band is defined as

$$[\tilde{\Gamma}_i - \tilde{\gamma}_i^-, \tilde{\Gamma}_i + \tilde{\gamma}_i^+). \quad (17)$$

If the $\tilde{\rho}_j$ value falls in any normalized threshold band, the adaptive adjustment algorithm in retransmission round is triggered.

For any nominal rate in the initial round, and for any given round j, the optimal threshold should make the remaining information bits successfully transmitted equally fast no matter using MCS_i or MCS_{i+1}. In other words, the normalized throughputs (normalized to the same number of remaining information bits) on both sides of the optimal threshold should be the same. Thus,

$$\tilde{\eta}_i(\tilde{\Gamma}_i) = R_i \times p_{A_i^{(j)}}(\tilde{\Gamma}_i) = \tilde{\eta}_{i+1}(\tilde{\Gamma}_i) = R_{i+1} \times p_{A_{i+1}^{(j)}}(\tilde{\Gamma}_i), \quad (18)$$

where $A_i^{(j)}$ means the event that the ACK signal is obtained when MCS_i is used in j-th retransmission round, and $p_{A_i^{(j)}}$ is the probability of $A_i^{(j)}$ defined similarly as in (5).

Based on similar derivations as in Section III-A, the MCS selection strategy in normalized threshold band can be derived and summarized as:

- If $A_i^{i(j)}$ happens, then select MCS_{i+1} the next time $\tilde{\rho}_j \in [\tilde{\Gamma}_i - \tilde{\gamma}_i^-, \tilde{\Gamma}_i + \tilde{\gamma}_i^+)$.
- If $A_{i+1}^{i(j)}$ happens, then select MCS_i the next time $\tilde{\rho}_j \in [\tilde{\Gamma}_i - \tilde{\gamma}_i^-, \tilde{\Gamma}_i + \tilde{\gamma}_i^+)$.
- Otherwise, when $\tilde{\rho}_j \in [\tilde{\Gamma}_i - \tilde{\gamma}_i^-, \tilde{\Gamma}_i + \tilde{\gamma}_i^+)$, the MCS is kept the same as the previous transmission.

Note that when the SNR does not fall in any threshold band, the MCS selection is regular, i.e., selecting MCS_i when the normalized SNR feedback is between $\tilde{\Gamma}_{i-1}$ and $\tilde{\Gamma}_i$. And the adaptive threshold value adjustment algorithm in retransmission round is:

- If $B_{i+1}^{i(j)}$ happens, then update $\tilde{\Gamma}_i$ with $\tilde{\Gamma}_i + \tilde{\delta}_{B_{i+1}^i}$,
- If $B_i^{i(j)}$ happens, then update $\tilde{\Gamma}_i$ with $\tilde{\Gamma}_i - \tilde{\delta}_{B_i^i}$,

where $\tilde{\delta}_{B_{i+1}^i}$ and $\tilde{\delta}_{B_i^i}$ are the step-size values for up and down adjustments, respectively, and the relationship between is the same as (12).

IV. Simulation Results

To verify the performance of the proposed algorithm, a simulation was done on a CDMA based system. The multiplexing technique used is code division multiplexing (CDM), the channel coding adopted here is turbo code (TC), and the HARQ type is IR. Four MCSs with nominal rates 1.0, 2.0, 3.0 and 4.5 are used in this system. The channel is generated using Jakes' model [12]. The detail parameters used in this simulation are summarized in Table I. All the simulations are run for 10000 frames and the the simulation time is enough to have convergence for all schemes. The simulation results under different mobile speed conditions are shown in Fig. 2 and Fig. 3. In both figures, the curve with triangular mark sketches the performance of the system with fixed MCS thresholds for the initial transmission, and the curve with cross mark presents the result of the system with adaptive thresholds for the initial transmission of each data frame. Both these curves are for non-adaptive HARQ, meaning, the MCS for the retransmission rounds is the same as that of the initial transmission. In addition, the curve with diamond mark is the result of the system with adaptive HARQ protocol and fixed thresholds, and the curve with circle mark is the result of the proposed method which adapts thresholds in both initial and retransmission rounds with adaptive HARQ protocol.

The simulation results with mobile speed $10km/hr$ are shown in Fig. 2. From the results shown in Fig. 2, it can be seen that the proposed adaptive threshold adjustment algorithm in HARQ retransmission rounds improves the throughput in most SNR region, and can get maximum about 0.5dB gain over the performance of the system only adapting MCS threshold in initial transmission while getting 2dB and 2.2dB gain over those of the fixed-threshold systems with adaptive and non-adaptive HARQ, respectively. Similarly, the simulation results with mobile speed $60km/hr$ in shown in Fig. 3. From the results shown in Fig. 3, it can be seen that the proposed adaptive threshold adjustment algorithm in HARQ retransmission rounds also improves the throughput in most SNR region with 1dB gain over the performance of the system only adapting MCS threshold in initial transmission while getting 2dB and 2.5dB gain over those of the fixed-threshold

TABLE I
PARAMETERS FOR SINGLE CARRIER CDM SIMULATION.

Parameter	Value
Multiplexing	CDM
Carrier Frequency	2GHz
Symbol Time Duration	0.667ms
Channel Model	Jakes' Model
Mobile Speed	10km/hr, 60km/hr
HARQ Type	IR
ACK/NACK Feedback delay	3 frames
SNR Feedback delay	6 frames
MCS	QPSK/$\frac{1}{2}$TC 16QAM/$\frac{1}{2}$TC 16QAM/$\frac{3}{4}$TC 64QAM/$\frac{3}{4}$TC
Maximum Retransmissions	7 rounds
Initial Thresholds	2dB, 5dB, 10dB
Step-size in Initial Transmission	0.75
Step-size in Retransmission	0.0025

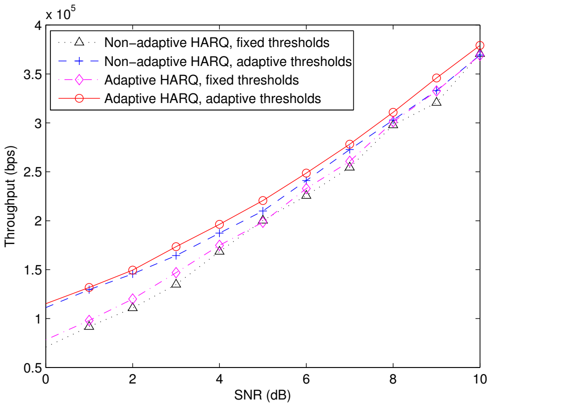

Fig. 2. Throughput of CDMA based system with mobile speed = 10km/hr.

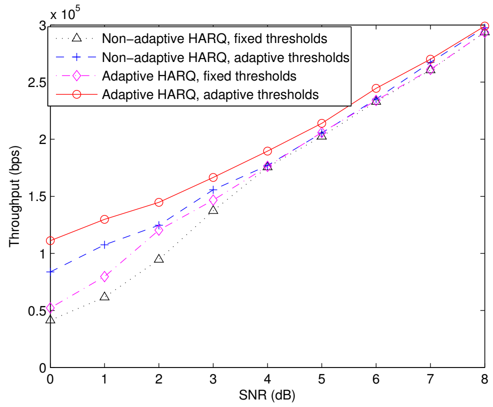

Fig. 3. Throughput of CDMA based system with mobile speed = 60km/hr.

systems with adaptive and non-adaptive HARQ, respectively. By comparing the results in Fig. 2 and Fig. 3, it can be seen that the proposed algorithm provides better performance gain under the condition of higher mobile speed. It is because that the channel variation is not so severe when mobile speed is slow, and therefore most of the data frames are received successfully at the initial transmission. On the other hand, if the mobile speed is fast, the proposed algorithm is able to trace and adapt the varying channel condition better. In addition, it can be seen that, in high SNR region, the curves seem to be merged. This is because only the MCS with highest rate is selected and the retransmissions seldom take place in high SNR region.

From the results and discussions above, it is clear that the proposed threshold adaptation algorithm indeed improves the system throughput when compared with the other two systems.

V. CONCLUSION

In this paper, we investigated the throughput maximization problem for AMC systems with HARQ. We first discussed the conditions for throughput maximization, and then proposed a novel algorithm capable of adaptively fulfilling these conditions. To generalize our discussion, it is assumed that adaptive HARQ protocol is used. Simulation results show that the proposed algorithm is very effective and has significant performance gain. This algorithm is very easy to implement, and can relieve the operators of different kinds of wireless communication systems using AMC and HARQ from having to perform offline optimization each time the channel statistics change.

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