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RESEARCH ARTICLE

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A cross-layer adaptive transmission scheme over correlated fading channels

Abstract Conventional adaptive transmission schemes perform poorly in wireless correlated slow-fading channels. A cross-layer adaptive transmission scheme combined with selective repeat automatic repeat request (SR-ARQ) is proposed. We apply a multi-state Markov system model for analyzing the performance of systems and optimizing the selection of modulation levels and packet sizes in correlated fading channels, which is also described by a finite-state Markov chain. A general closed-form expression of the average throughput for our suggested scheme is presented. Numerical results show that our adaptive scheme combined with SR-ARQ can obtain good performance in correlated fading channels.

Keywords adaptive modulation (AM), adaptive packet size (APS), automatic repeat request (ARQ), correlated fading channel, Markov channel

1 Introduction

Future wireless networks are expected to make efficient use of the radio resource to support realtime multimedia traffic. However, wireless links suffer from severe impairments such as path loss, multi-path effect and fading, which limit the overall system throughput considerably relative to wireline alternatives.

To promote the robustness and spectral efficiency in future wireless data communication systems, several adaptive transmission schemes combined with the ARQ technique have been studied extensively. Combining AM at the physical layer, which is an useful approach to achieve high spectral efficiency by selecting desirable modulation parameters such as constellation size and transmitted signal power depending on the current fading conditions, with ARQ has been a subject of investigation in recent years [1–5]. References [6–13] have studied another transmission scheme which combines adaptive packet (or frame) size (APS) with ARQ at the data link layer to mitigate channel fading. When SR-ARQ is employed, the optimal packet size to be used by the data link protocol is given by Ref. [14]

$$k_{\text{opt}} = \frac{-h\ln(1-p) - \sqrt{-4h\ln(1-p) + h^2\ln(1-p^2)}}{2\ln(1-p)} \quad (1)$$

where p is the known channel bit-error-rate (BER) and h is the number of overhead bits per packet. Unfortunately, however, it did not take the time varying characteristic of wireless channel into account. Falahati et al. [15] proposed a hybrid type-II ARQ schemes with adaptive modulation systems. In this scheme, accurate channel conditions need not to know and modulation modes are chosen just according to repeat requests. Liu et al. [16] adopted various modulation and coding schemes to reduce the packet delay according to packet sizes. Wu et al. [17] suggested a variable packet size adaptive modulation SR-ARQ scheme. As in most works, successive packet transmissions are assumed to be independent and identically distributed. However, consecutive block transmissions have high probability to be correlated, especially over a slow-fading channel. This correlation should not be neglected.

In this paper, considering AM at the physical layer and APS at the data link layer simultaneously, we proposed a cross-layer adaptive transmission scheme combined with SR-ARQ over correlated fading channels. It is denoted by APSAM/SR-ARQ hereafter. We apply a finite-state Markov channel (FSMC) model to substitute the two-state Gilbert-Elliott channel model to characterize the wireless nonstationary channel. Moreover, a Markov system model, an extension of the success/failure model, is used for analyzing the performance of APSAM/SR-ARQ, over correlated fading channels and optimizing the selection of packet sizes. In addition, a general closed-form expression of the average throughput for APSAM/SR-ARQ is provided. At last, this APSAM transmission scheme is compared to other ones.

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The remainder of the paper is organized as follows. Sect. 2 describes the configuration of APSAM/SR-ARQ scheme. A finite-state Markov channel model and N-failure/N-success process are presented in Sect. 3. Then we analyze the performance of APSAM/SR-ARQ systems and optimize the selection of packet sizes based on the Markov system model in Sect. 4. Simulation results are presented in Sect. 5. We conclude this paper in Sect. 6.

2 System configurations

In our adaptive transmission system, modulation levels and packet sizes are decided according to the channel condition for each user. The suggested adaptive transmission scheme and its analysis are based on TDMA systems, such as IEEE 802.16a, IEEE 802.16e, and other standards [18,19]. The simplified system is shown in Fig. 1. At the receiver, the signal level is measured, and based on the channel-state information the modulation mode and the packet size are decided to obtain maximum throughput efficiency. Then the corresponding transmission mode and ACK/NACK are sent to the transmitter via a feedback channel without error and latency. According to them, the transmitter sends new packets or retransmits the error packet. In this work, we assume that buffers at the transmitter and the receivers are both infinite and the transmitter always has perfect channel-state information.

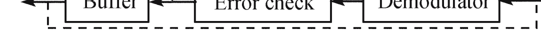

Fig. 1 Simplified system configuration

First, it is assumed that we have L different modulation levels, which form a modulation set $M = \{M_1, M_2,\dots, M_L\} = \{\text{BPSK, QPSK},\dots, \text{256-QAM}\}$. Based on the target BER requirement, we can find $L+1$ threshold values of receiver SNR [18], S_i, $i \in \{1, 2,\dots, L\}$, $S_0 = 0$, and $S_{L+1} = \infty$ with S_i as the threshold value of receiver SNR, using the ith-level modulation format. When the received SNR is low, packets are modulated with, for example, BPSK and when the channel condition improves and the received SNR is higher, QPSK or higher modulation levels can be used. In our analysis and simulations, when the SNR level is below S_1 a transmitter transmits packets using the lowest modulation level M_1 and the shortest packet size $N_{P_{\min}}$ (bits) in order to promote channel utilization.

We may use forward error correction (FEC) code along with adaptive packet size and modulation, as in IEEE 802.16a, IEEE 802.16e. Having FEC along with adaptive modulation and variable packet size will bring different SNR threshold for the same target packet-error rate (PER) requirement. Although FEC scheme is widely used for reliable communications, we only focus on how APSAM/SR-ARQ works and do not consider FEC codes in the following analysis and simulations. The adaptive transmission scheme, which combines these technologies, will be researched in the future.

3 Finite-state Markov channel and Markov model for APSAM

3.1 Channel model

In this paper, a correlated Rayleigh process is adopted for a slow-fading channel model. We assume that the average SNR at the receiver is kept as a constant by power control. The instantaneous receiver SNR γ has an exponential distribution with a probability distribution function (PDF) [21]. A finite-state Markov channel model can be built to represent the time-varying behavior of the Rayleigh fading channel. The received SNR values can be partitioned into a finite number of states and quantized to N levels with respect to the set of thresholds Γ_k, $k \in \{1, 2,\dots, N\}$, where assuming that the received SNR range is from 0 dB to ∞, so $\Gamma_1 = 0$ and $\Gamma_{N+1} = \infty$. The channel is in state k if the SNR is between Γ_k and Γ_{k+1}. These thresholds are different compared to S_i, $i \in \{0, 1,\dots, L\}$, used for the selection of modulation format earlier in Sect. 2. The FSMC model is presented in Fig. 2. For partitioning SNR levels, i.e., finding threshold values Γ_k, $k \in \{1, 2,\dots, N\}$ to complete the FSMC model, several methods have been used in Refs. [22–24]. Since the equal average duration method suggested by Ref. [22] can characterize the correlated fading channel better. In this work, we use this method for finding threshold values.

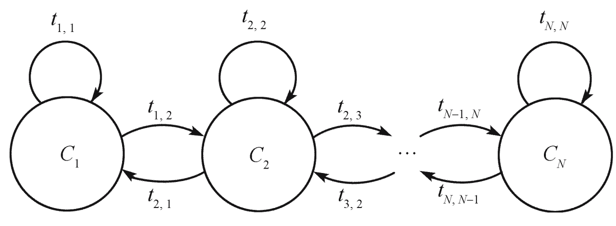

Fig. 2 Finite-state Markov channel model

According to the partition method, in order to make the average time duration of each state large enough to cover the packet time, considering the characteristics of TDMA systems, we can set $\overline{\tau}_k = cT_F$ with constant c (>1). In our work, we use a constant c between 3 and 8, as recommended in Ref. [22]. In addition, T_F is the duration of a TDMA frame and $\overline{\tau}_k$ is the average duration of received SNR interval (Γ_k, Γ_{k+1}). According to the level crossing rate and the expression equation of $\overline{\tau}_k$ (see Ref. [22]), we can find all threshold values Γ_k, $k \in \{1, 2,\dots, N\}$, ensuring that the SNR range of each state is equally large enough to cover the packet duration.

Once the number of states and corresponding SNR thresholds has been determined, we can calculate the transition probabilities for each state. As in Ref. [21], the transition from state C_k to state C_{k+1}, $t_{k,\,k+1} = \text{Prob}\{A_{n+1} = C_{k+1}\,|\,A_n = C_k\}$, can be approximated by the ratio of the level crossing rate at threshold Γ_{k+1} and the average number of packets per second staying in state C_k. Similarly, the transition probability $t_{k,\,k-1}$ is approximated by the ratio of the level crossing rate at Γ_k and the average number of packets per second staying in state C_k. Then the transition probabilities can be approximated as

$$\begin{cases} t_{k,k+1} \approx \dfrac{N(\Gamma_{k+1})}{\overline{n}_k} = \dfrac{N(\Gamma_{k+1})T_F}{\pi_k}, & k = 1,\ 2, \ldots, N-1 \\ t_{k,k-1} \approx \dfrac{N(\Gamma_k)}{\overline{n}_k} = \dfrac{N(\Gamma_k)T_F}{\pi_k}, & k = 2,\ 3, \ldots, N \\ t_{k,j} \approx 0, & |k-j| \geqslant 2 \\ t_{k,k} = 1 - \displaystyle\sum_{j=1, j\neq k}^{N} t_{k,j}, & k = 1,\ 2, \ldots, N \end{cases} \tag{2}$$

where π_k is the steady-state probability of each state. Hence, the transition matrix $\boldsymbol{T}$ can be represented as

$$\boldsymbol{T} = \begin{pmatrix} t_{1,1} & t_{1,2} & 0 & 0 & \cdots & 0 & 0 & 0 \\ t_{2,1} & t_{2,2} & t_{2,3} & 0 & \cdots & 0 & 0 & 0 \\ 0 & t_{3,2} & t_{3,3} & t_{3,4} & \cdots & 0 & 0 & 0 \\ 0 & 0 & t_{4,3} & t_{4,4} & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & t_{N-2,N-2} & t_{N-2,N-1} & 0 \\ 0 & 0 & 0 & 0 & \cdots & t_{N-1,N-2} & t_{N-1,N-1} & t_{N-1,N} \\ 0 & 0 & 0 & 0 & \cdots & 0 & t_{N,N-1} & t_{N,N} \end{pmatrix} \tag{3}$$

Now we calculate the PER and the average PER for each state. Due to a joint adaptive packet size and modulation scheme, each state will be assigned a specific modulation format and a given transmission packet size, which can bring the highest throughput efficiency. The PER and the average PER for each state can be defined respectively as

$$P_k^P(\gamma) = 1 - \left(1 - P_i^B(\gamma)\right)^{N_{P_k}} \tag{4}$$

$$\overline{P}_k^P \approx 1 - \left(1 - \overline{P}_{k,i}^B\right)^{N_{P_k}} \tag{5}$$

where $P_i^B(\gamma)$ is the exact BER of the ith modulation format, $\overline{P}_{k,i}^B$ is the approximate average BER of the ith modulation format in state C_k, $i \in \{1, 2, \ldots, L\}$, and $k \in \{1, 2, \ldots, N\}$. $\overline{P}_{k,i}^B = \int_{\Gamma_k}^{\Gamma_{k+1}} P_i^B(\gamma) f(\gamma)\,\mathrm{d}\gamma$

3.2 Markov system model for APSAM

In most literatures, a simplified Gilbert-Elliot model with "good" and "bad" states was often used to analyze the performance in wireless packet networks. However, just two states can not completely represent the behavior of fading channels, because the modulation format and packet size can be changed packet-by-packet, each packet may experience different spectral efficiency. As a result, we can model system with $2N$ state, dividing the good state into N different states which have different throughput efficiency values. Meanwhile, because of multiple transmission modes and the transition between adjacent states, the system can not transit from a "good" one to other unadjacent "good" ones by only one "bad" state. As Ref. [21], it is not accurate that the system has only one "bad" state. So, the bad state can also be partitioned into N states corresponding to errors in each channel state.

$$\begin{aligned} p_{B_k B_m} &= \text{Prob}\left\{\text{error } B_m \text{ at } t_{n+1} | \text{error } B_k \text{ at } t_n\right\} = \frac{\text{Prob}\left\{\text{error } B_m \text{ at } t_{n+1}, \text{ error } B_k \text{ at } t_n\right\}}{\text{Prob}\left\{\text{error } B_k \text{ at } t_n\right\}} \\ &= \frac{t_{k,m}\left[1-(1-\overline{P}_m^B)^{N_{P_k}}\right]\left\{t_{m,m-1}\left[1-(1-\overline{P}_{m-1}^B)^{N_{P_m}}\right]+t_{m,m}\left[1-(1-\overline{P}_m^B)^{N_{P_m}}\right]+t_{m,m+1}\left[1-(1-\overline{P}_{m+1}^B)^{N_{P_m}}\right]\right\}}{t_{k,k-1}\left[1-(1-\overline{P}_{k-1}^B)^{N_{P_k}}\right]+t_{k,k}\left[1-(1-\overline{P}_k^B)^{N_{P_k}}\right]+t_{k,k+1}\left[1-(1-\overline{P}_{k+1}^B)^{N_{P_k}}\right]} \end{aligned} \tag{6}$$

$$\begin{aligned} p_{B_k G_m} &= \text{Prob}\left\{G_m \text{ at } t_{n+1} | \text{error } B_k \text{ at } t_n\right\} = \frac{\text{Prob}\left\{\text{error } B_k \text{ at } t_n,\ G_m \text{ at } t_{n+1}\right\}}{\text{Prob}\left\{\text{error } B_k \text{ at } t_n\right\}} \\ &= \frac{t_{k,m}\left[1-^{N_{P_k}}\right]\left[t_{m,m-1}(1-\overline{P}_{m-1}^B)^{N_{P_m}}+t_{m,m}(1-\overline{P}_m^B)^{N_{P_m}}+t_{m,m+1}(1-\overline{P}_{m+1}^B)^{N_{P_m}}\right]}{t_{k,k-1}\left[1-(1-\overline{P}_{k-1}^B)^{N_{P_k}}\right]+t_{k,k}\left[1-(1-\overline{P}_k^B)^{N_{P_k}}\right]+t_{k,k+1}\left[1-(1-\overline{P}_{k+1}^B)^{N_{P_k}}\right]} \end{aligned} \tag{7}$$

$$\begin{aligned} p_{G_k B_m} &= \text{Prob}\left\{\text{error } B_m \text{ at } t_{n+1} \,|\, G_k \text{ at } t_n\right\} = \frac{\text{Prob}\left\{G_k \text{ at } t_n, \text{ error } B_m \text{ at } t_{n+1}\right\}}{\text{Prob}\left\{G_k \text{ at } t_n\right\}} \\ &= \frac{t_{k,m}(1-\overline{P}_m^B)^{N_{P_k}}\left\{t_{m,m-1}\left[1-(1-\overline{P}_{m-1}^B)^{N_{P_m}}\right]+t_{m,m}\left[1-(1-\overline{P}_m^B)^{N_{P_m}}\right]+t_{m,m+1}\left[1-(1-\overline{P}_{m+1}^B)^{N_{P_m}}\right]\right\}}{t_{k,k-1}(1-\overline{P}_{k-1}^B)^{N_{P_k}}+t_{k,k}(1-\overline{P}_k^B)^{N_{P_k}}+t_{k,k+1}(1-\overline{P}_{k+1}^B)^{N_{P_k}}} \end{aligned} \tag{8}$$

$$p_{G_kG_m} = \text{Prob}\{G_m \text{ at } t_{n+1} \mid G_k \text{ at } t_n\} = \frac{\text{Prob}\{G_k \text{ at } t_n, G_m \text{ at } t_{n+1}\}}{\text{Prob}\{G_k \text{ at } t_n\}}$$
$$= \frac{t_{k,m}(1-\bar{P}_m^B)^{N_{P_k}}\left[t_{m,m-1}(1-\bar{P}_{m-1}^B)^{N_{P_m}} + t_{m,m}(1-\bar{P}_m^B)^{N_{P_m}} + t_{m,m+1}(1-\bar{P}_{m+1}^B)^{N_{P_m}}\right]}{t_{k,k-1}(1-\bar{P}_{k-1}^B)^{N_{P_k}} + t_{k,k}(1-\bar{P}_k^B)^{N_{P_k}} + t_{k,k+1}(1-\bar{P}_{k+1}^B)^{N_{P_k}}} \tag{9}$$

$$\boldsymbol{P} = \left(\begin{array}{c|c} \boldsymbol{P}_{GG} & \boldsymbol{P}_{GB} \\ \hline \boldsymbol{P}_{BG} & \boldsymbol{P}_{BB} \end{array}\right)$$
$$= \left(\begin{array}{cccccc|cccccc}
p_{G_1G_1} & p_{G_1G_2} & 0 & \cdots & 0 & 0 & p_{G_1B_1} & p_{G_1B_2} & 0 & \cdots & 0 & 0 \\
p_{G_2G_1} & p_{G_2G_2} & p_{G_2G_3} & \cdots & 0 & 0 & p_{G_2B_1} & p_{G_2B_2} & p_{G_2B_3} & \cdots & 0 & 0 \\
0 & p_{G_3G_2} & p_{G_3G_3} & \cdots & 0 & 0 & 0 & p_{G_3B_2} & p_{G_3B_3} & \cdots & 0 & 0 \\
\vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & p_{G_{N-1}G_{N-1}} & p_{G_{N-1}G_N} & 0 & 0 & 0 & \cdots & p_{G_{N-1}B_{N-1}} & p_{G_{N-1}B_N} \\
0 & 0 & 0 & \cdots & p_{G_NG_{N-1}} & p_{G_NG_N} & 0 & 0 & 0 & \cdots & p_{G_NB_{N-1}} & p_{G_NB_N} \\
\hline
p_{B_1G_1} & p_{B_1G_2} & 0 & \cdots & 0 & 0 & p_{B_1B_1} & p_{B_1B_2} & 0 & \cdots & 0 & 0 \\
p_{B_2G_1} & p_{B_2G_2} & p_{B_2G_3} & \cdots & 0 & 0 & p_{B_2B_1} & p_{B_2B_2} & p_{B_2B_3} & \cdots & 0 & 0 \\
0 & p_{B_3G_2} & p_{B_3G_3} & \cdots & 0 & 0 & 0 & p_{B_3B_2} & p_{B_3B_3} & \cdots & 0 & 0 \\
\vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & p_{B_{N-1}G_{N-1}} & p_{B_{N-1}G_N} & 0 & 0 & 0 & \cdots & p_{B_{N-1}B_{N-1}} & p_{B_{N-1}B_N} \\
0 & 0 & 0 & \cdots & p_{B_NG_{N-1}} & p_{B_NG_N} & 0 & 0 & 0 & \cdots & p_{B_NB_{N-1}} & p_{B_NB_N}
\end{array}\right) \tag{10}$$

In the $2N$ states, G_k, $k \in \{1, 2,\ldots, N\}$, is represented as a state of success when modulation format M_i, $i \in \{1, 2,\ldots, L\}$, and packet size equaling to N_{P_k} are selected, while B_k is denoted as a state of failure. Figure 3 shows the Markov system model. As the above assumption that the channel-fading process transits only to the adjacent state, the transition in N-failure/N-success process occurs only between adjacent states. In order to obtain the transition probability matrix $\boldsymbol{P}$, we need to find elements of $\boldsymbol{P}$. As a result, $\boldsymbol{P}$ can be expressed as Eq. (10).

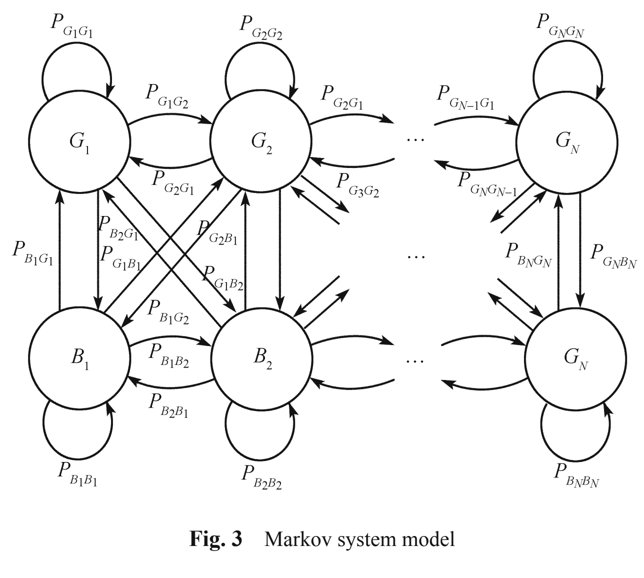

Fig. 3 Markov system model

With $\bar{\boldsymbol{p}} = \bar{\boldsymbol{p}} \times \boldsymbol{p}$ and $\sum_{i=1}^{N}\left(p_{G_i} + p_{B_i}\right) = 1$, we can find the steady-state probability $\boldsymbol{p} = (p_{G_1}, p_{G_2}, \ldots, p_{G_N}, p_{B_1}, p_{B_2}, \ldots, p_{B_N})$.

4 Performance of APSAM/SR-ARQ system and optimal selection of packet sizes

4.1 Analysis of system performance

We consider a slow-fading channel where fading level is a constant during a TDMA duration time which is guaranteed by the equal duration partitioning of the signal level, as in Sect. 3. We use the SNR to represent the channel status. In advance of analysis of system performance, we firstly assume that each erroneously received packet will be retransmitted immediately when acknowledged at the transmitter. Meanwhile, we assume that the feedback channel is error-free for ACK/NACK and that the transmitter buffer is always loaded for the next transmission, so that we can only see the effect of channel correlation and a cross-layer adaptive transmission scheme on the throughput performance of APSAM/SR-ARQ systems. Furthermore, we do not impose any restrictions on the number of retrials of a lost packet.

According to the above derivation and the N-failure/N-success Markov system model, the throughput of each state G_k, $k \in \{1, 2,\ldots, N\}$, is given by

$$\eta_k = \eta_k(N_{P_k}) = \int_{\Gamma_k}^{\Gamma_{k+1}} b_i\left[1 - P_k^P(\gamma)\right]\left(\frac{N_{P_k} - N_c}{N_{P_k}}\right) f_\gamma(\gamma)\mathrm{d}\gamma$$
$$\approx b_i\left[\left(1 - \bar{P}_{k,i}^B\right)^{N_{P_k}}\right]\left(\frac{N_{P_k} - N_c}{N_{P_k}}\right) \quad (11)$$

where N_c is the overhead of a packet and b_i is the number of bits transmitted in a symbol, i.e., the size of the constellation of the ith modulation level used in systems is 2^{b_i}, $k \in \{1, 2,\ldots, N\}$, and $i \in \{1, 2,\ldots, L\}$.

The analysis of our suggested scheme is based on TDMA systems. The wireless channel conditions are different for each user. Users transmit data on a wireless channel based on a time-division mode. So, it is reasonable that we optimize a user's average throughput substituting that of systems. Furthermore, the average throughput of APSAM/SR-ARQ systems can be expressed as

$$\bar{\boldsymbol{\eta}}_{\text{system}} = \boldsymbol{\eta} \times \boldsymbol{p}^{\mathrm{T}} = \sum_{k=1}^{N} \eta_{B_k} p_{B_k} + \sum_{k=1}^{N} \eta_{G_k} p_{G_k} = \sum_{k=1}^{N} \eta_{G_k} p_{G_k}$$
$$= \sum_{k=1}^{N} b_i\left[\left(1 - \bar{P}_{k,i}^B\right)^{N_{P_k}}\right]\left(\frac{N_{P_k} - N_c}{N_{P_k}}\right) p_{G_k} \quad (12)$$

where $\boldsymbol{p}^{\mathrm{T}}$ is the transpose of $\boldsymbol{p}$, $\boldsymbol{\eta} = \{\eta_{G_1}, \eta_{G_2}, \ldots, \eta_{G_N}, \eta_{B_1}, \eta_{B_2}, \ldots, \eta_{B_N}\}$ and η_{B_k} is the throughput of state B_k, $\eta_{B_k} = 0$.

4.2 Optimal selection of packet sizes

In this work, our target is to maximize the throughput performance $\boldsymbol{\eta}_{\text{system}}$ by using a cross-layer adaptive transmission scheme. According to the received SNR, the target BER and the thresholds of channel states, we can decide the modulation modes of the sender. After the modulation level has been determined at each channel state, there exists a problem how to optimize the packet size at the data link layer. In principle, this is a nonlinearly constrained optimization problem. It can be formulated as

$$\max_{N_{P_k}} \boldsymbol{\eta}_{\text{system}} = \sum_{k=1}^{N} b_i\left[\left(1 - \bar{P}_{k,i}^B\right)^{N_{P_k}}\right]\left(\frac{N_{P_k} - N_c}{N_{P_k}}\right) p_{G_k}$$
$$\text{subject to} \quad N_{P_{\min}} \leqslant N_{P_k} \leqslant N_{P_{\max}}$$
$$\text{for } k \in \{1, 2, \ldots, N\}, \ i \in \{1, 2, \ldots, L\} \quad (13)$$

On the reality that optimal solution cannot be easily achieved, sub-optimal one is obtained by using factor alternation algorithm [25]. This method is simple, intuitional, easy and controllable for approximation.

Now, we explain the factor alternation algorithm by depicting the calculations of the sub-optimal packet sizes of various states. First, we set the available minimum packet size as the initialization of each state, $\boldsymbol{x}_1^{(0)} = \{x_1^{(0)}, x_2^{(0)}, \ldots, x_N^{(0)}\}$. So, we can obtain the value of objective function, $\eta(\boldsymbol{x}_1^{(0)})$. Then, we search a better value $\boldsymbol{x}_1^{(1)}$ in the definition range of the first variable (i.e., the packet size of the first state) to get $\eta(\boldsymbol{x}_1^{(1)}) \geqslant \eta(\boldsymbol{x}_1^{(0)})$, where $\boldsymbol{x}_1^{(1)} = \{x_1^{(1)}, x_2^{(0)}, \ldots, x_N^{(0)}\}$. Furthermore, we search a better value $x_2^{(1)}$ in the definition range of the second variable (i.e., the packet size of the second state) to get $\eta(\boldsymbol{x}_1^{(2)}) \geqslant \eta(\boldsymbol{x}_1^{(1)})$, where $\boldsymbol{x}_1^{(2)} = \{x_1^{(1)}, x_2^{(1)}, x_3^{(0)}, \ldots, x_N^{(0)}\}$. As this method, we search all remanent variables and obtain $\eta(\boldsymbol{x}_1^{(N)}) \geqslant \ldots \eta(\boldsymbol{x}_1^{(1)}) \geqslant \eta(\boldsymbol{x}_1^{(0)})$, where $\boldsymbol{x}_1^{(N)} = \{x_1^{(1)}, x_2^{(1)}, x_3^{(1)}, \ldots, x_N^{(1)}\}$. Up to this, we have finished the first turn of search. Now, we begin the second turn of search regarding $\boldsymbol{x}_1^{(N)}$ as initializations. Until the difference between the initializations $\boldsymbol{x}_k^{(0)}) = (\boldsymbol{x}_{k-1}^{(N)}$ and the best values $\boldsymbol{x}_k^{(N)}$ in the kth turn is less than a certain ε, the algorithm has been searching. Here, we regard $\boldsymbol{x}_k^{(N)} = \{x_1^{(k)}, x_2^{(k)}, \ldots, x_N^{(k)}\}$ as the optimal solution $\boldsymbol{x}^* = \{x_1^*, x_2^*, \ldots, x_N^*\}$, i.e., the sub-optimal one of Eq. (13).

From the above analysis, we can find that the search step is a key to the runtime of algorithm and the approximate extent of sub-optimal one. We use MATLAB tools to simulate the factor alternation algorithm with four search steps to find a tradeoff between runtime and approximate extent. The range of a packet size is between 100 bits to 2 000 bits. The channel has twelve states. The runtimes and packet sizes for four search steps are listed in Table 1. Figure 4 shows the average throughputs of systems when packet sizes in various states are obtained by different search steps. Here, the parameters for the simulation are follows: the duration of TDMA frame 0.002 s (the duration can be 0.5, 1, 2 ms in IEEE 802.16a), vehicular speed of 5 km/h, carrier frequency of 2.4 GHz, the maximum Doppler frequency f_m of 11.111 1 Hz, the average received SNR 16 dB, $c = 4$ and packet overhead 48 bits. The minor differences among several curves are shown in this figure. Considering the runtime of algorithm, we use the search step 50 for sub-optimal packet sizes in the following simulations.

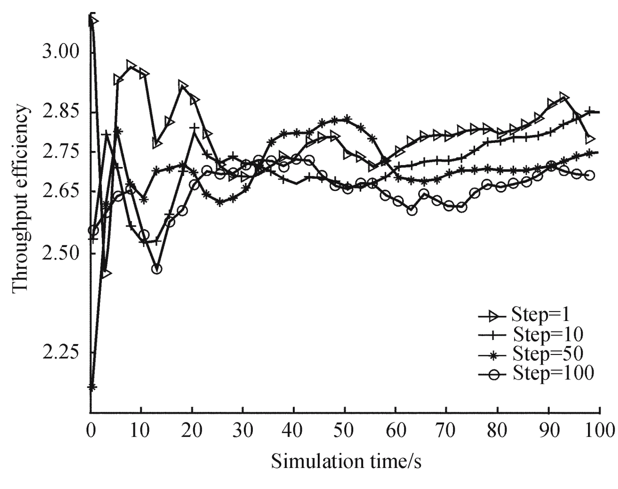

Fig. 4 Throughput vs. search step

Table 1 Packet sizes and runtime for different search steps

Search Step	State1	State2	State3	State4	State5	State6	State7	State8	State9	State10	State11	State12	Runtime
1	100	241	238	265	428	239	352	529	687	822	204	686	About 10 m
10	100	240	240	270	430	240	350	530	690	820	200	690	About 90 s
50	100	250	250	250	450	250	350	550	700	800	200	700	About 20 s
100	100	200	200	300	400	200	400	500	700	800	200	700	About 10 s

5 Simulation results

In the previous section, we have analyzed different search steps' effects, and found an appropriate step. In this section, simulation results about the performance of APSAM/SR-ARQ scheme are presented under different conditions. For simulations, a channel generator based on a modified Jakes' model [26] was developed to simulate the channel data profile. The parameters for the simulation are as follows: carrier frequency of 2.4 GHz, TDMA frame duration of 0.002 s, packet sizes between 100 bits and 2 000 bits, the average received SNR 16 dB, packet overhead 48 bits, vehicular speed 5 km/h and 10 km/h (i.e., nomadic mode in IEEE 802.16a). The c is 3 or 4.

When the vehicular speed is 5 km/h and the c is 4 in simulations, the maximum Doppler frequency f_m is 11.111 1 Hz. According to previous depicts, the wireless channel can be partitioned into twelve states. Table 2 lists the corresponding modulation levels for specific SNR intervals to satisfy the target BER. In this work, the target BER is 0.001. According to these simulation parameters and Table 2, the optimized switching thresholds are achieved with various modulation levels and packet sizes. They are shown in Table 3.

Table 2 SNR interval for different modulation levels (5 km/h)

Mode	Interval/dB	Modulation levels	Gain
M1	>6.444 9	BPSK	1
M2	>8.848 8	QPSK	2
M3	>11.199 9	8-QAM	3
M4	>14.238 6	16-QAM	4
M5	>17.971 6	32-QAM	5
M6	>24.026 5	64-QAM	6

Table 3 Optimized switching thresholds (5 km/h, $c=4$)

Channel state	Γ_k/dB	Selected modulation levels	Average BER	N_{P_k}/b
State 1	0–7.508 2	BPSK	0.129 2	100
State 2	7.508 2–11.483 4	QPSK	5.125 4e–4	250
State 3	11.483 4–14.210 3	8-QAM	5.402 5e–4	250
State 4	14.210 3–16.292 5	16-QAM	4.283 2e–4	250
State 5	15.292 5–17.981 5	16-QAM	1.047 2e–4	450
State 6	17.981 5–19.407 5	32-QAM	5.863 1e–4	250
State 7	19.407 5–20.644 5	32-QAM	2.031 5e–5	350
State 8	20.644 5–21.740 3	32-QAM	8.637 2e–5	550
State 9	21.740 3–22.726 2	32-QAM	5.309 1e–5	700
State 10	22.726 2–23.640 6	32-QAM	2.001 3e–5	800
State 11	23.640 6–24.502 0	64-QAM	8.720 3e–4	200
State 12	24.502 0–∞	64-QAM	4.492 0e–5	700

In Fig. 5, the throughputs of APSAM/SR-ARQ system, adaptive modulation system with fixed packet sizes and adaptive packet size system with fixed modulation levels over a Rayleigh correlative fading channel are compared. Due to the character of channels, excessively large packet size results in increase of PER and deterioration of system performance in adaptive modulation system with fixed packet sizes. At the meantime, although adaptive packet size system with fixed modulation levels can improve the throughput, but fixed modulation levels can not adapt the diverse channel conditions. From this figure, we observe that our APSAM scheme is superior to other two adaptive transmission schemes over the correlated slow fading channel. Its steady-state throughput can be maintained a higher level because our APSAM scheme can match channel perfectly.

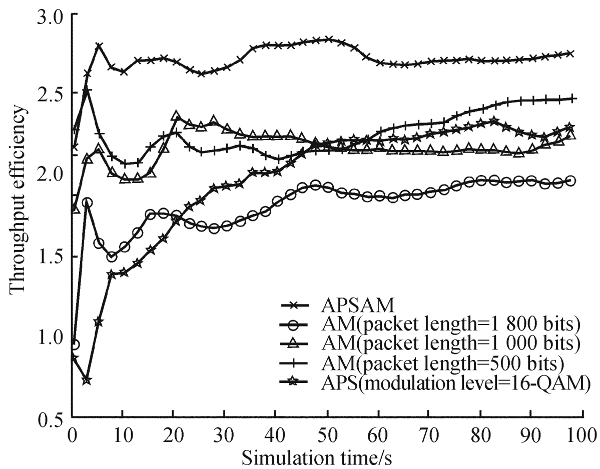

Fig. 5 Throughput of various adaptive schemes (5 km/h, $c=4$)

Tables 4–6 list the corresponding modulation levels for specific SNR intervals and the optimized switching thresholds when the vehicular speed is 10 km/h and the c is 4 or 3. From these tables, it can be found that different c will affect the average duration of each channel state and result in different number of states. If c is larger, packets stay in each state longer and a smaller number of states are obtained for the Markov model for a fixed f_mT_F. The product of f_mT_F characterizes the fading speed of the channel relative to the TDMA frame length. The number of states has an effect on the precision of channel characterization. From Figs. 6 and 7, we obtain that higher throughput is achieved when $c=3$. The reason is that the APSAM scheme can match channel more perfectly with more states. However, too small c may result

Table 4 SNR interval for different modulation levels (10 km/h)

Mode	Interval/dB	Modulation levels	Gain
Mode 1	> 7.682 0	BPSK	1
Mode 2	> 9.534 2	QPSK	2
Mode 3	> 13.002 6	8-QAM	3
Mode 4	> 15.834 6	16-QAM	4
Mode 5	> 19.735 1	32-QAM	5
Mode 6	> 25.132 1	64-QAM	6

Table 5 Optimized switching thresholds (10 km/h, $c = 4$)

Channel state	Γ_k/ dB	Selected modulation levels	Average BER	N_{P_k}/b
State 1	0–11.112 9	BPSK	0.04268	100
State 2	11.112 9–15.926 9	QPSK	7.391e-5	550
State 3	15.926 9–19.141 4	16-QAM	3.9246e-4	300
State 4	19.141 4–21.681 8	32-QAM	5.672e-4	250
State 5	21.681 8–24.053 4	32-QAM	1.6287e-4	350
State 6	24.053 4–∞	64-QAM	3.716e-5	800

Table 6 Optimized switching thresholds (10 km/h, $c = 3$)

Channel state	Γ_k/dB	Selected modulation levels	Average BER	N_{P_k}/b
State 1	0–9.570 2	BPSK	0.090 2	100
State 2	9.570 2–14.047 1	8-QAM	9.705e-4	200
State 3	14.047 1–17.030 5	16-QAM	4.361e-4	250
State 4	17.030 5–19.299 6	16-QAM	1.601 4e-4	350
State 5	19.299 6–21.162 3	32-QAM	4.027e-4	300
State 6	21.162 3–22.777 9	32-QAM	1.938 1e-4	350
State 7	22.777 9–24.266 5	32-QAM	7.752e-5	550
State 8	24.266 5–∞	64-QAM	3.118e-5	900

in excessive channel states. This brings out that one packet can experience different channel states. Appropriate c is very important.

Comparing Fig. 5 with Fig. 7, we see that the throughput of APSAM scheme is higher in Fig. 5. The reason is that faster vehicular speed results in larger f_m. Furthermore, the number of states is smaller if $f_m T_F$ increases and less of the dynamics of the channel are captured. The channel behaves like a fast fading channel. When the vehicular speed is slower, the fading speed of the channel relative to the TDMA frame length, $f_m T_F$, is slower and suggested APSAM scheme can obtain better system performances. That also illustrates that the APSAM/SR-ARQ scheme can work better over correlated slow-fading channels.

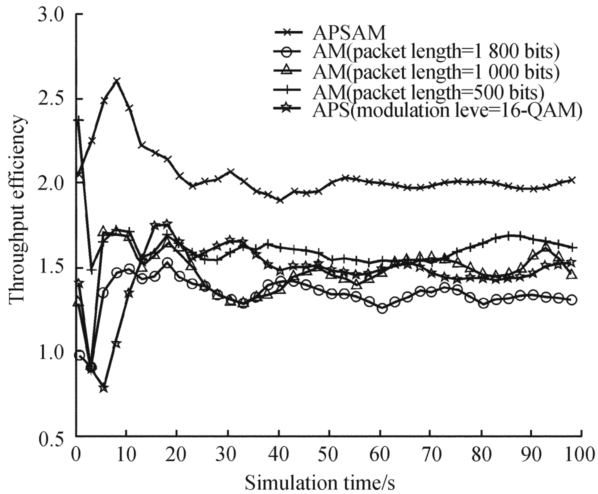

Fig. 6 Throughput of various adaptive schemes (10 km/h, $c = 4$)

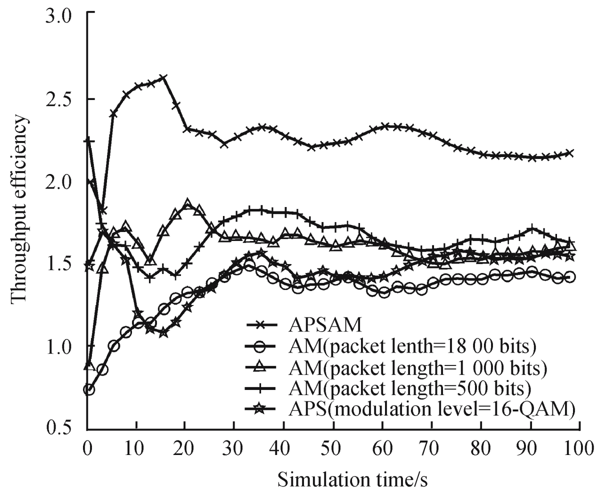

Fig. 7 Throughput of various adaptive schemes (10 km/h, $c = 3$)

6 Conclusions

In this paper, we developed an adaptive transmission scheme APSAM/SR-ARQ over correlated slow-fading channels. Instead of two-state Gilbert-Elliott channels, we adopt a finite-state Markov channel model to characterize the correlated fading channel by using an equal-duration partitions method suggested in Ref. [22]. Meanwhile, we apply a Markov system model to analyze the performance of APSAM/SR-ARQ systems and optimize the selection of modulation levels at the physical layer and packet sizes at the data link layer. A general closed-form expression of the average throughput for APSAM/SR-ARQ is presented. Numerical results show that our adaptive transmission scheme in SR-ARQ system can improve performance of conventional ARQ with fixed modulation levels or fixed packet sizes over correlated slow-fading channels. In the future, we will study the new adaptive transmission scheme, which combines three technologies of AM, APS and adaptive FEC, to further improve the system performance.

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