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An MDP Based Energy Efficient Transmission Policy for Wireless Terminals

Xiao-Hui Lin, Yi-De Huang, Chao Yang, Ning Xie, Bin Chen, Shengli Zhang, Hui Wang

Faculty of Information Engineering, ShenZhen University, China
Email: xhlin@szu.edu.cn

ABSTRACT

In wireless network, terminals are usually energy constrained. In order to extend the lifetime of the terminal, the limited energy must be utilized in an efficient manner. In this paper, under the constant transmission power scenario, we propose an Energy Efficient Transmission Policy (EETP) which is derived by using Markov Decision Process (MDP). The simulation results show that compared with the Threshold Transmission Policy (TTP), the proposed policy can reduce the energy consumption significantly, while satisfying the performance demand at the same time.

1. Introduction

Wireless communication systems have deeply penetrated into our daily life and the wireless terminals such as smart phone, tablet PC and wireless sensor node have brought fundamental changes to our society. However, the design of wireless system is a challenging task, in which, many issues must be properly handled. Among these design issues, one of the most crucial one is energy-efficiency of wireless system.

In literature, there have been a lot of research works on the design of energy-efficient communication systems. The design philosophy is usually to achieve the required level of performance by consuming just enough energy.Specifically, in [1], Uysal-Biyikoglu formulates the problem as how to minimize the energy consumption while satisfying the delay constraints at the same time. In order to reduce the energy consumption, In [2] based on the queue length in the system, Curt Schurgers proposed a traffic adaptive technique called Dynamic Modulation Scaling (DMS) which adaptively change the modulation level to lower the overall energy consumption, while bounding the packet delay at an acceptable level. In[3], Baris Ata studies how to control the transmitting power based on the buffer state. The objective is to minimize long-run average energy consumption subject to a QoS constraint, which is expressed as an upper bound on the packet loss rate. Author also formulates the issue into a Lagrangian problem and derives the optimal power control policy.

In [4], Liu analyzes the cross-layer design of AMC system. Specifically, both the queue length and channel state have been considered. By deriving the stationary probability of the system state, Liu gives a performance analysis model and develops a cross-layer design method. The work is novel, but the author doesn't consider the energy issue. In this paper, we adopt the Liu's method in the performance analysis and try to design an energy efficient transmission system.

2. System Model

2.1. Markov Model for Wireless Channels and AMC

In this paper, we focus on the uplink transmission. Terminals transmit data to base station through wireless channel. We assume the channel is a block fading channel. It means that the channel is frequency flat, and remains invariant per frame, but is allowed to vary from frame to frame, which is suitable for slowing varying wireless channel. And we adopt Finite State Markov Channel (FSMC) model to describe the channel. FSMC is a popular model adopted in literature [4-6]. Specifically, the channel quality can be captured by the received signal-to-noise ratio (SNR). By partitioning the range of the received SNR into a finite number of intervals, a finite-state model for the fading channel is built [7]. We use $\{S_n\}, n = 0, 1, \ldots N$ to denote the different state of the channel, and let $A_0 < A_1 < A_2 \cdots < A_{N+1}$ be the thresholds of different state. If the instantaneous received SNR is between A_k and A_{k+1}, we will say the channel is in state S_k. Based on the method in [4-7], we can get the channel state transition probability matrix P_c.

In our study, we adopt the adaptive physical layer design called ABICM [8], in which variable throughput modulator and channel coding are used. We assume a 4-mode AMC configuration is used. Therefore, there are four distinctive throughputs available as listed in **Table 1**. We divide the channel into five different states $\{S_0; S_1; S_2; S_3; S_4\}$ according to the instantaneous channel quality. Note that when channel is in state S_0, no packet is sent because the channel is in deep fading. So if the feedback CSI falls within the interval $\{A_k; A_{k+1}\}$ $k = 0,1,2,3,4$, transmission mode k is selected.

The processing unit at the data link layer is packet that includes multiple information bits. And each packet at this layer is assumed to contain a fixed number of bits (NP). At physical layer, the information delivery is performed in a frame-by-frame manner. And in physical layer, the symbol rate (RS) and the frame duration are assumed to be constant, which means that each frame contains a fixed number of symbols (Ns).

Therefore, based on the modulation and coding rate pair adopted in **Table 1**, we can find that the number of packets one frame can carry is 1:2:4:8. Since the transmit power is constant, the energy needed to transmit one packet under different modes is 8:4:2:1. So we should transmit in higher mode as much as possible to conserve energy.

2.2. Buffer Queuing Analysis

In [4], authors originally propose a discrete time queuing analysis method which is also used in the performance analysis in our paper, with some emendations made to fit the situations in our work. The queuing model is illustrated in **Figure 1**.

Table 1. AMC system.

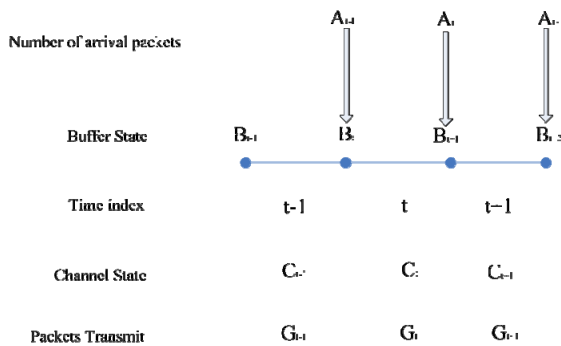|	Mode1	Mode2	Mode3	Mode4
Modulation	QPSKK	8PSK	32QAM	512QAM
Coding rate	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{4}{5}$	$\frac{8}{9}$
bits/symbol	1	2	4	8
ThresholdAk	5.016	10.035	13.826	17.381

Figure 1. Queuing model.

Let t denote the time units and A_t the number of packets arriving at time t. The time unit in our study is frame duration T_f. For simplicity, let the arrival process be

$$A_t = a \quad for\ all\ t \quad (1)$$

Let B_t denote the buffer state which is the number of packets currently stored in the buffer. Thus we have

$$B_t \in \mathbf{B} \qquad \mathbf{B} = \{0, 1, 2, 3 \cdots K\} \quad (2)$$

We use C_t to denote the channel state at time t, which can be written as

$$C_t \in \mathbf{C} \qquad \mathbf{C} = \{S_0, S_1, S_2, \cdots S_N\} \quad (3)$$

In our study, we use buffer state B_t and channel state C_t to form a state pair (C_t, B_t). The number of packet that one time unit can transmit is highly related with the system state (C_t, B_t). We use G_t to denote the action (i.e. number of packets to transmit) we can select at time t, thus we have

$$G_t \in \mathbf{G} \qquad \mathbf{G} = \{0, 1, \cdots \min(C_t, B_t)\} \quad (4)$$

At any time t, based on the B_t, C_t, G_t and A_t, we can get B_{t+1} by

$$B_{t+1} = B_t - G_t + A_t \quad (5)$$

Then we can get the queue state transition probability as

$$Pb(B_{t+1} | (C_t, B_t), G_t) = \begin{cases} 1 \ if\ G_t \in G\ \&\ B_j = B_i + A_t - G_t \\ \\ 0\ otherwise \end{cases} \quad (6)$$

G_t can be decided by the transmission policy g, which indicates how many packets we should transmit under the current system state. When we have the system state (C_t, B_t), guided by the transmission policy g, we can get the transmission decision $G_t = g(C_t, B_t)$. Then the buffer transition probability (6) can be calculated.

In order to understand the system better, we need to derive the system state transition probability and stationary distribution. Since the channel process and queue process are independent with each other, based on Pc and (6) we can get the system state transition probability

$$P((C_t+1, B_t+1)|(C_t, B_t), G_t)$$
$$= P_C(C_t+1|C_t) \qquad P_B(B_{t+1}|B_t, g(C_t, B_t)) \quad (7)$$

Based on the method proposed in [4] (24-26), we can derive the stationary distribution Pg(c, b), (c, b) ∈ C × B under the transmission policy g.

Then we can calculate the desired performance under different transmission policy and find the optimal one. The packet loss rate Pd is [4] (27-30):

$$E[D] = \sum max[0, a - K + (b - g(c, b))] * P\mathbf{g}(c,b) \quad (8)$$
$$c \in C; b \in B$$

$$P_d = \frac{E[D]}{a} P_d \quad (9)$$

And the expected energy consumed per frame under the transmission policy **g** can be calculated by

$$\widetilde{E} = \sum_{(c,b)\in C\times B} P(c,b)E_c g(c,b) \qquad (10)$$

where Ec is the energy cost for transmit one packet under the channel state c.

3. MDP Formulation

Based on the analysis given in previous sections, the system state can be described as a state pair (Ct;Bt) where Ct is the channel state and Bt is the buffer state at time t. After we get the system state, we can select an action from the action space $G_t \in G = \{0; 1; ....; \min(C_t;B_t)\}$. And we know that the state transition probability depends on the action selected. Therefore, the problem can be modeled as a Markov Decision Process (MDP) [10]. Next we should construct a cost function to derive the optimal transmission policy by using MDP.

Since in the transmission policy design, we need to consider two factors-energy consumption and the level of QoS achieved, the cost function is constructed with both factors taken into consideration:

$$R((c,b),g(c,b)) = E_c * g(c,b) + \beta * \frac{5^2}{K^2} * (b-g(c,b))^2 \quad (11)$$

Note that equation (11) is dimensionless. The first term in (11) is the energy cost for packet transmission with the transmission policy g. Since the buffer is finite, we assume that when the buffer is full, the newly arriving packets are simply dropped, which can incur packet loss and delay. Therefore the second term in (11) is a penalty cost. We replace the constraint on QoS with a penalty cost for packet storing. From the second term, we can see that the penalty cost is in quadratic growth with the number of packet stored. $\beta \in [0, 1]$ is a weight factor, representing the relative importance of the QoS, therefore, the larger β the higher QoS demand.

Our objective is to find a transmission policy g* which can minimize the overall cost, which is called value function V. Specifically, optimal transmission policy can be written as:

$$\mathbf{g}^* = \arg\min_{\mathbf{g}\in\Pi} \mathbf{V^g}$$
$$= \arg\min_{\mathbf{g}\in\Pi} E^{\mathbf{g}}_{(c,b)}[\sum_{t=0}^{\infty} \lambda^t R((c_t,b_t), g(c_t,b_t))] \qquad (12)$$

where Π is all possible policy space, and λ is a discount factor. Since the system evolves in a stochastic manner, we should calculate the expectation of overall cost. We let Eg(c,b) denotes the expectation cost under the policy g. The policy g* above is called the optimal policy, and the related cost function Vg* under the policy g* is called the optimal discounted value function.

This problem is an infinite horizon discounted cost problem. It can be solved by the numerical method called Policy Iteration Algorithm.

4. Numerical Simulation Results

In this section, we perform extensive simulations to validate the proposed policy. The simulation parameters are listed in **Table 2**:

The weight factor β in (11) indicates the QoS demand. We vary the value of β from 0 to 1. Based on the method we propose in section 3, we get the optimal transmission policies with different β. Then the system transition probability (7) and stationary distribution of the system can be calculated. With the stationary distribution, we can evaluate the performance of the optimal transmission policy under different β by using (9-10). Then we get the packet loss rate and expected energy consumed under the different QoS demand β. The impact of different under different average received SNR is illustrated in **Figures 2-5**.

Table 2. Simulation parameters for.

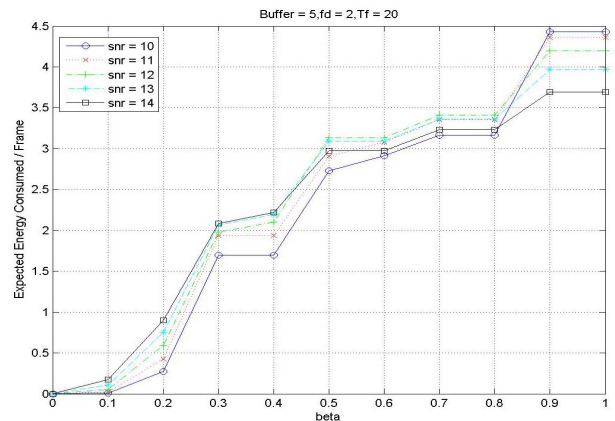| Parameter	Value
Symbol Rate R_s	200ksymbol/s
Packet Size L_p	4000bit
Frame Duration T_f	20ms
Dopple Frequency f_d	2Hz
Buffer Size K	5
Arrival Process Parameter a	1
Average received SNR Υ_0	$\Upsilon_0 \in [10, 19]$
Initial Battery Energy	100Joule
ES$_4$	10^{-3}Joule

Figure 2. Expected energy consumed per frame versus beta (Average received SNR=[10,11,12,13,14]).
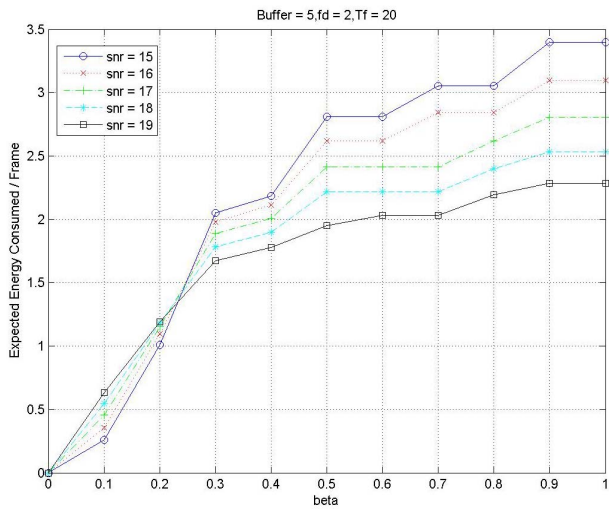
Figure 3. Expected energy consumed per frame versus beta (Average received SNR =[15,16,17,18,19]).
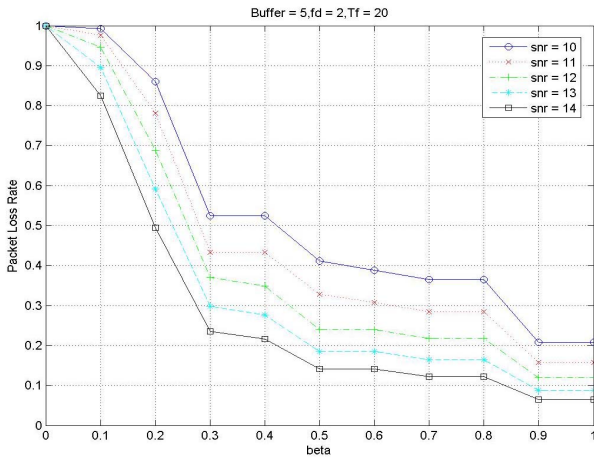

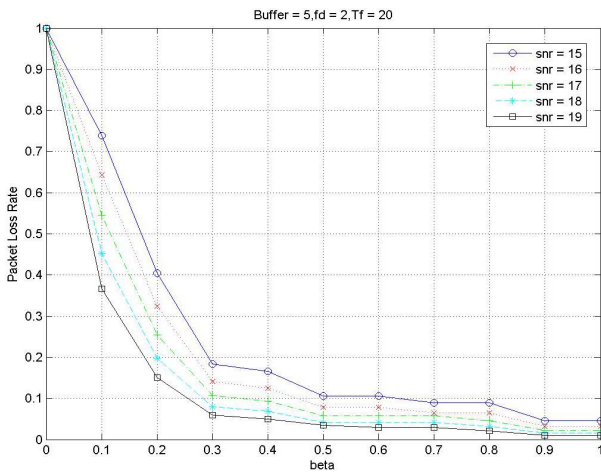**Figure 4. Packet loss rate versus beta(Average received SNR = [10, 11, 12,13, 14]).**

Figure 5. Packet loss rate versus beta (Average received SNR = [15, 16, 17,18, 19]).

In the **Figure2-3** we can observe that the expected energy consumed per frame increases with β, which indicates that when the QoS demand increases, the penalty for buffering the packet increases as well. It is unwise to store the packet in buffer, because the storing cost is higher than that of transmission cost, even we transmit the packet under a low mode. Hence system should transmit packet as much as possible no matter what transmit mode it would adopt. However when become small, the storing cost is relatively smaller than the transmit cost. Therefore, system would prefer packet storing rather than transmission, and wait until the channel quality recover.

From the **Figures 4-5** we can observe that the packet loss rate decreases with β, which means that by varying β , we can achieve different levels of QoS. Joint with **Figures 2-3** we can see the tradeoff between energy and QoS, i.e. Higher energy consumption means a better QoS.

Next, we compare our Energy-Efficient Transmission Policy (EETP) with Threshold Transmission Policy (TTP) [8].

The average received SNR = 15dB. Under the Threshold Transmission Policy, only when the received SNR is above the threshold A_k can we transmit packets. The system transmits packet in a best effort manner. Then we have 4 different transmission policies under the Threshold Transmission Policy, among which, we can select the best one.

However, compared with TTP, more policy strategies are provided in our method, and thus search space is much larger. Consequently, we can further reduce the energy consumption with better policy as illustrated in **Figure 6.**
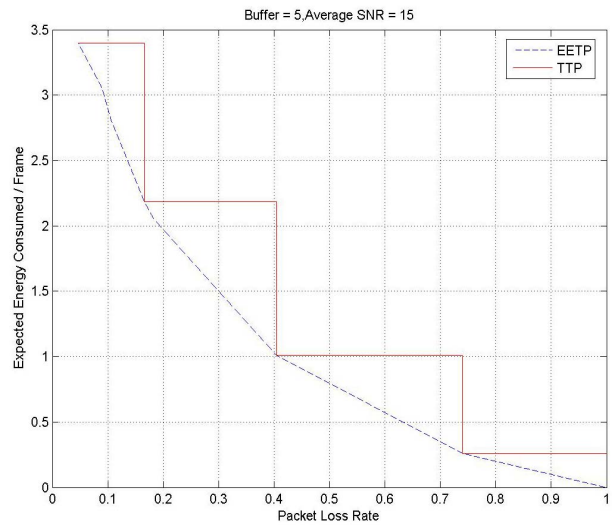

Figure 6. Energy Efficient Transmission Policy versus Threshold Transmission Policy.

5. Conclusions

In this paper, we study the energy efficient transmission under the constant transmission power constraint. We formulate the Energy Efficient Transmission Problem as a MDP problem and use the Policy Iteration Algorithm to get the optimal transmission policy which consumes the least amount of energy while achieving the QoS demand. We compare our method with previous threshold method. Simulation results show that our transmission policy can reduce the energy consumption significantly.

6. Acknowledgements

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