Buffer Control using Adaptive MQAM for Wireless Channels

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Abstract: We consider the problem of buffer control in wireless communication using adaptive transmission techniques. In our model, a transmitter at the physical layer has a buffer with fixed length and bits arrive into the buffer according to a Poisson distribution. A server takes bits out of the buffer, maps them into M-ary quadrature amplitude modulation (MQAM) symbols for transmission through a wireless link. We assume that the server can vary the data rate by changing the constellation size of its MQAM modulator. Our objective is to maintain the reliability of transmission, with respect to the required bit error rate (BER) at the receiver and the required buffer overflow probability (BOP), while minimizing average transmit power. We obtain the solution to this problem using dynamic programming and use simulation to show that the obtained solution provides a considerable gain in terms of average transmit power relative to less-adaptive transmission schemes.

Keywords: buffer control, adaptive modulation, dynamic programming.

1. INTRODUCTION

In mobile wireless communication, guaranteeing performance in terms of delay, loss and throughput is an important issue. To do so usually requires a trade off between quality of service and scarce system resources such as bandwidth, buffer space and transmit power. This motivates us to look at the problem of buffer control for wireless communication.

We consider a simple server in which bits are mapped into transmitted symbols using M-ary quadrature amplitude modulation (MQAM). Modulated

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symbols are transmitted at a fixed rate through a wireless channel. Suppose that for reliable communication, a certain received bit error rate (BER) is required. If we want to increase the rate at which bits are transmitted from the buffer, the signal constellation size needs to be increased. This will result in more transmit power needed for maintaining the required BER. Of course, how fast bits are transmitted from the buffer affects the buffer overflow probability (BOP) and the objective is to maintain a certain BOP and BER while minimizing average transmit power.

Our research is inspired by the works of Berry and Gallager [1] and Goldsmith and Chua [2]. In [1], the problem of adapting transmission rate and power based on channel and buffer states under queuing delay constraints has been studied. Concentrating on the regime of asymptotically large delay, the authors have characterized simple buffer control policies which exhibit optimal performances. In [2], a variable-rate, variable-power MQAM modulation scheme for high-speed data transmission over fading channels has been proposed. By adapting the signal constellation size to the channel condition, the authors have shown that there is a 5-10 dB power gain relative to less adaptive transmission schemes.

What makes our work different from [1] is that we study the problem in a more practical context in which the buffer length is reasonably small and the data transmission rate is controlled by an adaptive MQAM modulator. What makes our work different from [2] is that we take into account both channel state and buffer occupancy. We use dynamic programming [3], [5] to solve for the optimal adaptive transmission policy and show, by simulation, that the policy obtained gives us a performance gain over less-adaptive schemes. We first solve the problem for an AWGN channel and then show that the policy obtained can be extended for a fading environment.

Our paper is organized as follows. In section II, we give the system model and briefly describe how the server works. In section III, the optimization problem is defined. In section IV, which is the main part of this paper, we present the dynamic programming approach and a simple algorithm that can be used to search for the optimal adaptive policy. In section V, numerical results and discussion are provided. Finally, we give a conclusion for the paper and indicate potential avenues for further research.

2. SYSTEM MODEL

The system model in Figure 1 represents a mobile terminal transmitting data traffic through a dedicated wireless link. We first start with a simple AWGN channel model. Later, we will argue that the solution obtained can be extended for fading environment. We define the following parameters:

- λ is the average arrival rate (bits/sec), the arrival process is Poisson;
- L is the buffer length (bits);
- M is the signal constellation size of the MQAM modulator;
- T_s is the symbol period (sec);
- W is the channel bandwidth (Hz) and ;
- σ^2 is the power spectral density of the AWGN channel;

Figure 1. System model of a mobile terminal transmitting data over a wireless channel.

We assume the transmitter functions as follows. The time axis is divided into periods of length T_s . During the k^{th} period, bits arrive at the buffer and queue up. At the end of this period, a decision is made on how many bits should be mapped into the QAM symbol s_k for transmission in the next period. During the $(k+1)^{\text{th}}$ period, while the symbol s_k is being transmitted, new bits arrive and queue up in the buffer and the process is repeated.

3. PROBLEM DEFINITION

Our objective is to minimize the average transmit power while maintaining the required BER and BOP. Since it is often difficult to get a closed-form expression for the BER and BOP, we use upper bounds and numerical techniques instead. As mentioned above, we first start with an AWGN channel model.

3.1 Maintaining Required BER

In [4], for MQAM modulation and ideal coherent phase detection, given the received signal to noise ratio (SNR), the BER for an AWGN channel is bounded by

$$BER \leq 2e^{-1.5SNR/(M-1)} \quad (1)$$

It is also stated in [2] that for $M \geq 4$ and $0 \leq SNR \leq 30 \text{ dB}$, a tighter bound for BER is

$$BER \leq 0.2e^{-1.5SNR/(M-1)} \quad (2)$$

Without loss of generality, we assume that the noise power is unity. From (1), the transmit power needed for transmitting i bits of information while guaranteeing certain value of BER is

$$Pw(i) \geq \log(-0.5BER)(2^i - 1) / 1.5 \quad (3)$$

Similarly, from (2), we have

$$Pw(i) \geq \log(-5BER)(2^i - 1) / 1.5 \quad (4)$$

In this paper, we will use (3) and (4) to approximate the power needed to transmit i bits of information using MQAM.

3.2 Maintaining Required BOP

The buffer can be represented by a discrete-time Markov model in which a state i ($i = 0, 1, \dots, L$) means there are i bits in queue at the end of a symbol period. Let $\mathbf{r} = [r_i]$ be a policy that transmits r_i bits when the buffer is in state i . Clearly, we must have r_i less than or equal to i . The transition probability from state i to state j is

$$\begin{aligned} P_{ij} &= A_{j-i+r_i} && \text{for } (i-r_i) \leq j < L, \\ P_{iL} &= 1 - \sum_{k=0}^{L-i+r_i-1} A_k && \text{for } j = L, \\ P_{ij} &= 0 && \text{otherwise.} \end{aligned} \quad (5)$$

Here A_k is the probability that k bits arrive at the buffer during a symbol period. For an arrival process with a Poisson distribution

$$A_k = \frac{1}{k!} e^{-\lambda T_s} (\lambda T_s)^k. \quad (6)$$

Let p_i ($i = 0, 1, \dots, L$) be the steady state probability that there are i bits in the buffer and $\mathbf{p} = [p_i]$. Also, let $\mathbf{P} = [P_{ij}]$ be the transition probability matrix. The quantity $\mathbf{p}$ can be calculated from

$$\mathbf{p} = \mathbf{p} \mathbf{P} \quad \text{or} \quad \mathbf{p}(\mathbf{P} - \mathbf{I}) = \mathbf{0}, \quad (7)$$

with $\mathbf{I}$ and $\mathbf{0}$ are the $L \times L$ identity matrix and $L \times 1$ zero vector respectively. The steady state buffer overflow probability is

$$P_{of} = \sum_{i=0}^L (p_i \sum_{j=L-i+1}^{\infty} A_j). \quad (8)$$

3.3 Optimization Problem

Using all of the above derivations, our optimization problem can be defined as follows:

$$\begin{aligned} &\text{minimize over all policies } \mathbf{r}: && P_{avr} = \sum_{i=0}^{i=L} P_w(r_i) p_i, \\ &\text{subject to:} && P_{of} \leq BOF \end{aligned} \quad (9)$$

Due to high complexity, we cannot solve for a closed-form expression for $\mathbf{r}$. In the next section, we propose an algorithm that can be used to search for $\mathbf{r}$ numerically.

4. DYNAMIC PROGRAMMING APPROACH

4.1 Average Cost Problem

Instead of solving (9) directly, let us consider a related problem of finding a policy r which minimizes a weighted sum of the average transmit power and the buffer overflow probability (given the same constraint on the BER):

$$\text{minimize over all policies } r: \quad C(\beta) = P_{avr} + \beta P_{of}. \quad (10)$$

Here β is a positive scalar. Let r^* be the transmission policy which minimizes (10) for a certain value of β and P_{avr}^* and P_{of}^* be the corresponding values of the average transmit power and the buffer overflow probability. It is easy to see that P_{avr}^* is the minimum average transmit power needed to guarantee that the buffer overflow probability is not more than P_{of}^* . So for each value of β , by solving (10) we obtain a point on the optimum power-BOP curve.

The optimization problem of (10) is called an average cost problem. With finite numbers of buffer states and control policies, there is always a stationary solution to (10). In fact, (10) can be solved using dynamic programming techniques [3], [5].

4.2 Proposed Algorithm

The basic idea behind the dynamic programming approach is to convert our optimization task into a shortest path routing problem. This can be done by considering each buffer state as a node in a graph and assigning a cost to each transition from one node to another. The cost here is the weighted sum of transmit power and probability of buffer overflow. By using various shortest path routing algorithms that are available in the literature, we can find the optimal solution to (10).

Here, we propose an algorithm that searches for the policy r that minimizes (10) over a period of length T . For a mobile terminal, T can be thought of as the length of a particular active period. We usually have T to be quite large; it is of the order of thousands of the symbol period T_s . A shortest path search is carried out in the reverse direction of time, starting from $t = T$ and going back until $t = 0$.

We initially set $t = T$ and set the cost of each node $c_k(T) = 0$, $k = 0, 1 \dots L$. At time t , suppose that the buffer is in state k and we decide to transmit i bits. The incurred cost is the sum of the transmit power, $P_w(i)$, the overflow probability when there are $k - i$ bits in the buffer, (scaled by β),

$$\beta \sum_{l=L-k+i+1}^{\infty} A_l,$$

and the expected costs that have been accumulated up to time $t + 1$,

$$\sum_{j=0}^L P_{(k-i)j} C_j(t+1).$$

At each time t and for each buffer state k , the number of bits being transmitted i should be chosen so that the incurred cost is minimized. The proposed algorithm is:

Algorithm

Parameters:

$\mathbf{r}(t) = [r_0(t), r_1(t), \dots, r_L(t)]$ is the transmission policy obtained at time t .

$\mathbf{r}^0$ is the final policy obtained by the algorithm.

$\mathbf{c}(t) = [c_0(t), c_1(t), \dots, c_L(t)]$ is the cost of each node at time t .

$P_w(i)$ is the power to transmit i bits of information, calculated by (3) and (4).

P_{ij} is the transition probability from state i to state j , calculated by (5).

A_l is the probability of l bits arriving to the buffer during a symbol period, calculated by (6).

Initialization:

$t = T$, and $c_k(T) = 0$ for $k = 0, 1, \dots, L$;

Iteration steps:

Step 1: $t = t - 1$;

Step 2: For $k = 0, 1, \dots, L$,

$$r_k(t) = \arg \min_{i=0,1,\dots,k} \left\{ P_w(i) + \sum_{j=0}^L P_{(k-i)j} c_j(t+1) + \beta \sum_{l=L-k+i+1}^{\infty} A_l \right\}$$

$$c_k(t) = P_w(r_k) + \sum_{j=0}^L P_{(k-r_k)j} c_j(t+1) + \beta \sum_{l=L-k+r_k+1}^{\infty} A_l$$

Step 3: If $t = 0$ set $\mathbf{r}^0 = \mathbf{r}(0)$ and finish, else go back to Step 1;

We have run numerical tests and the above algorithm always converges to a fixed policy after a small number of the iteration steps. Therefore, we need not run the iteration until $t = 0$. The fixed policy to which the iteration converges is the stationary optimal solution to (10).

5. NUMERICAL RESULTS AND DISCUSSION

5.1 Numerical Results

First, we compare the performance of the adaptive scheme (obtained by the algorithm proposed above) with that of the “less-adaptive” ones. We consider two less-adaptive transmission schemes which are called “Dummy” and “Fixed”. The “Dummy” scheme transmits bits at a fixed rate. In case there are not enough bits in the buffer, dummy bits will be transmitted. It is clear that this scheme is very inefficient. In the “Fixed” scheme, a maximum rate is set for the server. If the number of bits in the buffer is not enough for transmission at the maximum rate, the server only transmits whatever is available in the buffer.

Figure 2. Overflow probability versus average transmit power for adaptive, fixed and dummy schemes ($L = 12$ bits, $\lambda = 30$ kbps, $T_s = 0.1$ ms, $W = 10$ kHz and $BER = 10^{-3}$).

Figure 3. Overflow probability versus average transmit power for adaptive and fixed schemes ($L = 30$ bits, $\lambda = 30$ kbps, $T_s = 0.1$ ms, $W = 10$ kHz and $BER = 10^{-3}$).

In Figure 2, the performances of the three schemes are plotted for the following system parameters: $L = 12$ bits, $\lambda = 30$ kbps, $T_s = 0.1$ ms, $W = 10$ kHz and $BER = 10^{-3}$.

It is clear that the adaptive scheme always performs better than the "Dummy" and "Fixed" ones and the "Dummy" scheme is the most inefficient policy. However, we note that the gain of the adaptive scheme relative to the "Fixed" one is not very large. When the buffer overflow probability is from 10^{-3} to 10^{-4} , the gain in the average transmit power is only from 0.5 to 1 dB.

Next, we plot the performances of adaptive and "Fixed" schemes under the case when the buffer length is very large. For the buffer length of 30 bits and the other system parameters are kept as before, the performances of the two schemes are shown in Figure 3. As can be seen, the advantage of the adaptive scheme over the "Fixed" scheme is much clearer in this set up.

5.2 Extending the Solution for Fading Channels

The optimal policy we have obtained for AWGN channels can be extended for block fading channels. Under the block fading assumption, within one block of channel use, the channel gain is unchanged. In this case, within each fading

block, the channel can be treated as an AWGN channel with the received SNR being scaled by the constant channel gain. If the requirement is that at every fading state, the upper bound of the BOP must be met then we can use the same algorithm proposed before to search for the optimal policy within each channel state.

For the cases when the required BOP is averaged over all fading states or when a channel is under fast fading, work is currently being carried out. In Figure 4, the performances of three different schemes under fading environment are shown. The fading channel is represented by a ten-state Markov chain. The three schemes being tested are “fixed-rate, fixed-power”, “fixed-rate, inverted-power” and “adaptive-rate, adaptive-power”. The “adaptive-rate, adaptive-power” has been obtained by a search algorithm similar to the one proposed above. As can be seen, the adaptive technique offers a performance gain in terms of transmit power relative to less adaptive ones.

Figure 4. Overflow probability versus average transmit power for three different schemes under ten-state Rayleigh fading channel.

6. CONCLUSION

In this paper, we study the problem of buffer control for wireless communication. We have found out that by adapting the transmission rate (via changing the MQAM constellation size) to the buffer state and the channel condition, the power needed to reliably transmit data and to keep buffer overflow probability low can be minimized. Finally, we note that further work is needed in terms of analysis and dealing with fast fading channel conditions.

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