Buffer Control for Communication over Fading Channels

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Abstract — **We consider a user communicating over a flat fading channel. The user wishes to reliably communicate bursty data over this channel while minimizing both the average power and the average delay incurred. We formulate a buffer control problem which illustrates the trade-off between these quantities. This model is analyzed using dynamic programming techniques. The asymptotic performance is shown and asymptotically optimal buffer control policies are given.**

I. Introduction

Motivated by wireless communication, channel models where the output conditionally depends on a time-varying channel state have received much attention. Cases where either the transmitter or receiver have access to channel state information (CSI) have been well studied. Using the CSI, the transmitter can allocate communication resources over time in an effort to combat the fading. In this work, we study such resource allocation problems for a single user in a flat fading channel when both the transmitter and the receiver have perfect CSI. The goal is to minimize the transmission power required to provide the user with an acceptable quality of service. Minimizing power is an important consideration since mobile users rely on batteries with limited energy.

If the user simply required a long term average rate, then minimizing the average power needed to communicate reliably is equivalent to characterizing the channel's capacity. This has been well studied for a large class of fading channels. Approaching the capacity of a fading channel, typically requires the use of codewords whose length is long enough to average over the channel statistics. We consider the situation where in addition to an average rate, the user requires a given average delay. When delay constraints limit codeword lengths, then capacity may not be a *useful* performance criterion; *i.e.* one can not get an acceptable probability of error at rates near capacity while satisfying the delay constraint. This is the motivation behind the work on outage capacity and delay-limited capacity. We also assume that messages arrive from a higher layer protocol in a bursty manner and are placed into a transmission buffer. Delay requirements may prevent one from removing this burstiness through source coding.

We consider the following model. Assume that the messages are fixed length packets of $\log M$ bits which arrive from some higher layer application and are placed into a transmission buffer. Let A_n be the number of packets that arrive at time n, where $\{A_n\}$ is an ergodic Markov chain with steady-state average arrival rate $\bar{A}$. Periodically, the transmitter removes a packet from the buffer, encodes it into one of M codewords of infinite length, and begins transmitting the codeword over a fading channel. Assume the channel is a complex, additive white Gaussian noise channel with a time-varying gain $H_n \in \mathbb{C}$. The process $\{H_n\}$ is also modeled as an ergodic Markov chain. While transmitting, the transmitter can adjust the transmission energy by scaling the input by an adjustable gain. This decision is based on the channel state, the buffer occupancy and the current source state. Once the receiver can decode the message with an acceptable probability of error, the transmitter stops transmitting the packet and proceeds to the next packet. We formulate a new buffer model where the buffer occupancy corresponds to the amount of error exponent required by each packet; this is a variation of the model used in [1]. At each time U_n, the amount of exponent to be transmitted, is chosen. A given choice of U_n requires $P(H_n, U_n)$ average transmission energy.

We consider the problem of minimizing the average transmission power subject to a given average delay constraint. Let $P^*(D)$ be the minimum average power required for the average delay to be less that D. We show that $P^*(\cdot)$ is always a non-increasing convex function. Each point of $P^*(D)$ can be found by minimizing

$$\lim_{n\to\infty} \frac{1}{m}\sum_{i=1}^{m} P(H_n, U_n) + \beta\frac{S_n}{\bar{A}}$$

for an appropriate choice of β. Here S_n corresponds to the buffer occupancy at time n. This corresponds to solving an average cost dynamic programming problem where the cost is a weighted sum of the average power and average delay.

We study the behavior of $P^*(D)$ as $D \to \infty$. Our approach to this problem is similar to the work in [2] on buffer control for variable rate lossy compression. The mathematical structure underlying these problems has many similarities. Let $\mathcal{P}(\bar{A})$ denote the limiting value of $P^*(D)$. We characterize $\mathcal{P}$ and show that $P^*(D) - \mathcal{P}(\bar{A}) = \Theta(1/D^2)$. Finally a sequence of *simple policies* is given which exhibit this optimal convergence rate. These policies have the characteristic that the transmission rate is a function only of the the channel state and in which of two regions the current buffer state lies.

References

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