Higher Layer Perspectives on Modeling the Wireless Channel

Ramesh R. Rao
Dept. of Electrical Engineering and Computer Engineering, University of California, San Diego,
9500 Gilman Drive, La Jolla, CA, 92093-0407
e-mail: rrao@ucsd.edu

Abstract — We present recent findings that reveal the importance of higher order error statistics in assessing the impact of particular forms of error control on services as seen by the higher layers of a protocol stack. In an effort to generalize our past work on the sensitivity of higher layer protocols to channel errors, we examine ways to capture the behavior of realistic channels with tractable models. We examine the property of weak lumpability of Markov Chains as well as apply stochastic bounding techniques to previously published channel models and develop analytical techniques that are especially relevant from the perspective of the higher layers of a protocol stack.

I. INTRODUCTION

Although error control schemes have been studied extensively over the years, the focus is usually on throughput and average bit error rate. Such characterizations appear to be inadequate in understanding the impact of error control schemes especially when the focus shifts from the transfer of bits on the physical channel to the exchange of higher layer protocol entities. In our talk, we present some of our recent results that reveal the importance of higher order error statistics in assessing the impact of particular forms of error control on higher layer services. We also address the challenge of capturing the behavior of realistic channels with tractable models.

II. BLOCK ERRORS OVER TIME VARYING CHANNELS

Errors that occur on the wireless channel are a function of specific propagation artifacts such as multi path, fading and user mobility. The traditional metric used for characterizing such channel errors, is the average bit error rate. From the perspective of higher layer applications, raw channel variations are not directly useful. A more relevant quantity is block errors, since many if not all applications run atop of a link-layer that exchanges blocks of data.

We present upper and lower bounds for block error probabilities when bit transmissions occur over a channel that is characterized only by its second order statistics with no further assumptions about its structure. We assumed that a binary bit sequence, $X_n$, is transmitted across a stationery, time varying wireless channel that induces a binary bit error sequence $E_n$, resulting in a received bit sequence $D_n = E_n \oplus X_n$. An element $E_i = 1$ corresponds to an error in the received bit $D_i$. The error sequence, $E_n$, that results from these time varying phenomenon is not IID in general. It is assumed that the mean, variance and correlation of the stationary sequence, $E_n$.

We consider the effect of $E_n$ on the sensitivity of higher layer protocols such as TCP. There have been several recent investigations on different facets of wireless TCP. However, most of these studies do not consider the effect of correlation in multipath fading on the performance of TCP over wireless. We shall describe recent work on the performance of TCP over a fading channel based on a model that is designed to capture end-to-end performance of wide-area connections that contain a wireless link only on the last hop. We developed upper and lower bounds by relaxing particular rules of the protocol. The evolution of these two bounding processes is determined by the interaction of the deterministic TCP window evolution and the error process on the channel that was assumed to be Markov.

The results show that the throughput of TCP is significantly affected not only by the average error rate but also by the second-order error statistics. For a fixed average error rate, TCP Tahoe performs better over channels with longer bursts. The frequency of error events (which cause a slow start phase to be initiated) has a much bigger impact than the number of packet errors involved in such events. These considerations could be very helpful in designing coding and interleaving schemes.

Our studies at the link and transport layer revealed that the higher order characteristics of errors is crucial to understanding the impact of a particular channel on higher layer protocols. It is natural then to seek better models for the channels. At the same time, the analysis of higher layer protocols can get to be very difficult if the channel characteristics are complex. There is thus a need for approaches to channel modeling that are both tractable and accurate.
IV. MODELING WIRELESS CHANNELS

The results described above highlight the need for accurate channel models. Although more general than the IID model, the 2-state channel model is known to be inadequate for the representation of some time-varying channels. One way of overcoming this problem is to enlarge the number of states. Fritchman in 1963 investigated a finite-state Markov chain with model with N (N ≥ 2) states. The state space was then partitioned into two groups with Group A corresponding to k error-free states and Group B corresponding to N−k error states. Fritchman’s model has been applied by many researchers to represent error sequences obtained over the HF ionospheric channel, the Rayleigh fading channel [5] and the wireless indoor channel [6]. Although a large number of states provides a better representation of the channel, the complexity of the model makes the system performance analysis mathematical intractable. It is therefore worth investigating if we can simplify the representation by reducing N-state model makes the system performance analysis mathematical intractable. It is therefore worth investigating if we can simplify the representation by reducing N-state model to a 2-states Markov chain and at the same time maintain a better representation of the channel. We shall outline two approaches in this regard, involving the notions of weak lumpability and hazard rate ordering.

A. WEAKLY LUMPABLE CHAINS

Let X be a homogeneous, irreducible, discrete-time Markov chain on a finite-state space denoted by S, which without loss of generality we assume to be a subset of the natural numbers N. S = {1, 2, ..., N}. The process X has an aperiodic transition matrix P with an equilibrium distribution denoted by a row vector π and initial probability vector η ∈ A where A is the set of all probability vectors. Let Ω = {ω(1), ω(2), ..., ω(M)} with M < N be a fixed partition of the state space S.

With the given process X and the partition Ω, we can associate the aggregated stochastic process Y with values on S = {1, 2, ..., M}, defined by Y(ω) = m if X(n) ∈ ω(m), ∀n ≥ 0.

Conditions under which the aggregated stochastic process agg(ω(1), ω(2), ..., ω(M)) is an homogeneous Markov chain were studied by Burke and Rosenblatt in 1959 [1], Hachgian in 1963 [2], and Kemeny and Snell in 1967 [3]. Such a chain that has this property is called strong lumping with respect to the partition Ω. A more general problem is to determine if there exists some initial distributions α such that agg(ω(1), ω(2), ..., ω(M)) is a homogeneous Markov chain but not necessarily for every vector of A. The Markov chain, in this case, is called weakly lumpable with respect to the partition Ω.

Weak lumpability was first studied by Kemeny and Snell in 1976 [3], where they showed that it is possible that there exists a proper subset AM of the set of all initial probability vector A such that the aggregated process Y is a homogeneous Markov if and only if α ∈ AM. Kemeny and Snell also provided a simple but strong sufficient condition for weak lumpability. Rubin and Sericola in 1991 [4] obtained a characterization of weak lumpability by means of an algorithm which computes the set AM of initial distributions and gave necessary and sufficient conditions for weak lumpability. Lumpability of a Markov chain with a denumerable state space was first discussed by Hachgian in 1963 [2]. Rubin and Sericola in [4] gave an algorithm to compute the set AM. In our application, the initial distribution vector is always the steady state distribution vector, i.e., α = π. Hence, proving that there exists a proper subset AM is sufficient, since AM = ∅ =⇒ π ∈ AM.

B. STOCHASTIC BOUNDS

The second approach is to stochastically bound, from above and below, more complex channel availability processes with exponentially distributed On-Off Process. In particular the following theorem due to Miller [7] is invaluable.

Let {S, i = 0, 1, 2, ...} be a renewal process with interarrival cumulative distribution function F which has failure rate function r(t), i.e., Let r0 and r1 be a right-continuous function such that sup s→∞ r(s) ≤ r0(s) ≤ ∞ and inf s→∞ r(s) ≥ r1(t) > 0 for t ≥ 0, respectively. Then there exist nonhomogeneous Poisson processes {T0, i = 0, 1, 2, ...} and {T1, i = 0, 1, 2, ...} with cumulative mean function A0(t) = ∫0t r0(s)ds and A1(t) = ∫0t r1(s)ds on the same probability space as {S, i = 0, 1, 2, ...} such that {T0, T0′, T1′, T2, ..., } and {S0, S1, S2, ..., } and {T0′, T1′, T2, ..., } ⊂ {S0, S1, S2, ..., } almost surely, respectively.

Concrete comparison criteria that depend on hazard rate ordering of random variables can now be obtained from this result. The task reduces to computing the hazard rate, of the actual On-Off distributions and identifying if these curves can be bounded by constants. If so, the upper and lower bounds to the hazard rate correspond to parameters of exponentially distributed (a.s.) bounding On-Off process. These bounds can in turn be used to predict the performance of higher layer protocols.

V. RESULTS

We shall conclude by examining higher order channel models (involving up to eight states) that have been published in the literature by Sivaprasakam [6], Wang and Moyaeri [5] and identify if any of them are weakly lumpable and work out the parameters of the bounding on-off processes.

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REFERENCES


