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Performance modeling of finite state Markov chains for Nakagami-q and α–μ distributions over adaptive modulation and coding schemes

Vidhyacharan Bhaskar*, Nagireddy Peram

Department of Electronics and Communication Engineering, SRM University, Kattankulathur, Tamilnadu 603203, India

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ABSTRACT

In this paper, performance modeling of finite state Markov chain (FSMC) for Nakagami-q and α–μ fading distributions over adaptive modulation and coding (AMC) schemes at the physical layer are discussed in detail, assuming that sufficient data is present to be transmitted continuously during the adaptive transmission period. However, this assumption is not always valid when queuing effects are taken into account at the data link layer. The received SNR obtained from a coded multiuser wireless system in the presence of a heavily shadowed environment is assumed to undergo a Nakagami-q (Hoyt distribution. Performance measures like level crossing rate, steady state probability, state transition probability and state time duration for Nakagami-q distribution and α–μ distribution are derived, plotted and analyzed. The BER for non-coherent FSK is shown to be much better than coherent FSK and PSK in the presence of Nakagami-q fading.

1. Introduction

1.1. Overview

In multimedia wired or wireless communication networks, the demand for high data rates and quality of service (QoS) is growing at a rapid pace. The “bottleneck” in such networks is the wireless link not only because wireless resources (bandwidth and power) are scarce and expensive relative to their wired counterparts, but also because overall system performance degrades markedly due to fading, Doppler, and time-dispersive effects introduced by multipath.

1.2. Literature review

To enhance spectrum efficiency while adhering to a target error performance over wireless channels, adaptive modulation and coding (AMC) has been widely used to match transmission parameters to time-varying channel conditions [1–5]. Due to its good rate and error performance characteristics, AMC has been adopted at the physical layer of several wireless standards, such as 3GPP, 3GPP2, HIPERLAN/2, IEEE 802.11a, IEEE 802.15.3, and IEEE 802.16 [6–8].

In [9], FSMC is used to model fading channels in mobile radio communications, where each state in the FSMC represents a range of received Signal-to-Noise Ratios (SNRs). In [10], the notion of fading channel memory order is best explained in auto regressive (AR) modeling of time varying flat fading channels (TV-FFC). These mathematical models are necessary to accurately describe time variations of fading channel gain and its dynamics. Selection of amplitude region boundaries that determine accuracy and applicability of the obtained FSMC model is discussed in [11].

In [12], a FSMC is used to represent received SNRs having Log-normal, K and Chi-square distributions. Performance measures like level crossing rate, state transition probability, steady state probability are derived. The work carried out in [13] describes first order FSMC models that can be obtained for fading channels, and also discusses its applications. However, existing AMC schemes rely on the salient assumption that is continuously available at the transmitter. This assumption is not always valid when queuing effects are taken into account at the data link layer. In this paper, the joint effects of finite length queuing and AMC for transmission over wireless links are analyzed. This paper addresses the effect of amplitude on the FSMC modeling of TV-FFC.

In [14], a study of the second-order statistics of Nakagami–Hoyt fading channel model was considered wherein expressions related to finite-state channel modeling, like level crossing rate, and average duration of the fades are derived. A simple and efficient deterministic simulation model based on Rice’s sum of sinusoids, which enables the emulation of the fading envelope of the Nakagami-q model with the desired statistics, was also described.

In [15], a method for selecting the parameters of a finite-state Markov chain to match slow fading channels that are characterized by Nakagami-m fading probability distributions was presented. The

* Corresponding author.
E-mail addresses: meetvidhyacharan@yahoo.com, vcharan@gmail.com (V. Bhaskar), nagireddy09@gmail.com (N. Peram).

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Nakagami fading parameter, m, and the correlation parameter for fade levels experiences by consecutive symbols or packets can be adjusted to match anticipated propagation conditions or experimental data.

A first-order Markov model for generalized Nakagami-m (1960) flat fading channels was proposed in [16]. The usefulness of the proposed Markov model is illustrated by applying it to the analysis of the throughput and energy efficiency performance of a link layer (LL) protocol with back-off on wireless fading links with different values of m-parameter (=0.5, 1, 4).

A relatively new small-scale multipath fading model, namely, the α–μ fading distribution was presented in [17]. Closed-form expressions for the amount of fading (AoF) and average channel capacity for this channel model reduce to other expressions for other channel models as special cases. In [18], a new infinite series representation for multi-variate α–μ joint density function was derived, allowing for an arbitrary matrix and non-identically distributed variates. The formulation is general and exact, and comprises all other joint densities that arise from α–μ distribution published in literature. Average error probability for coherent and non-coherent modulation schemes over α–μ distributions are presented in [19]. Numerical results are presented to show the effect of correlation between received desired signals and interference on system performance.

Performance evaluations for practical protocols typically require simulation of both time-varying fading process and the adaptive protocol. The authors developed [20] finite-state Markov models of Nakagami-m fading to obtain analytical evaluations of throughput of adaptive coding protocol.

1.3. Organization of the paper

The rest of this paper is organized as follows: Section 2 presents the Multiuser system model. The expressions for probability of choosing modulation, packet error rate (PER), steady state probability, level crossing rate, state time duration and state transition probability are presented in Section 3. Numerical results are presented in Section IV. Finally, Section 4 concludes this paper.

2. System model

Fig. 1 illustrates an end-to-end connection between a server (source) and a subscriber (destination), which includes a wireless link with a single-transmit and a single-receive antenna. Downlink system is focussed here, although our results are applicable to uplink systems as well.

A finite length queue (buffer) is implemented at the transmitter, and operates in a first-in-first-out (FIFO) basis. The queue feeds the AMC controller at the transmitter. The AMC selector is implemented at the receiver. We assume that multiple transmission modes are available, with each mode representing a pair of specific modulation formats, and a forward error correction (FEC) code, as in HIPERLAN/2 and IEEE 802.11a standards. Based on the channel state information (CSI) available at the receiver, the AMC selector determines the modulation-coding pair (mode), which is sent back to the transmitter through a feedback channel, for the AMC controller to update the transmission mode. Coherent demodulation and maximum-likelihood (ML) decoding are employed at the receiver. The decoded bit streams are mapped to packets, which are pushed upwards to layers above the physical layer.

2.1. Assumptions

1. The channel is frequency flat, and remains invariant per frame, but is allowed to vary from one frame to another. Here, a frame is a group of packets which contains data. This corresponds to a block fading model which is suitable for slowly varying channels. As a consequence, AMC is adjusted on a frame-by-frame basis [21].
2. Perfect CSI is available at the receiver using training-based channel estimation. The corresponding mode selection is fed back to the transmitter without error and latency.
3. If the queue is full, the additional arriving packets will be dropped, and will not be recovered by end-to-end (server-to-subscriber), or link-layer retransmissions. This can be afforded by the User Datagram Protocol (UDP), for instance, where retransmission can be denied when delay or buffer-size constraints are violated [21].
4. Error detection based on CRC is perfect, provided that sufficiently reliable error detection CRC codes are used. The packet header and the CRC parity bits per packet are not included in the throughput calculation because they introduce negligible redundancy relative to the number of payload bits.
5. If a packet is not received correctly at the receiver after error detection, it is dropped, and a packet loss is declared [21].

The contribution of this work lies in finite-state modeling of received SNRs, which are assumed to follow a Nakagami-q (Hoyt) distribution. Using finite-state modeling, several performance measures, like steady-state probability, state transition probability, level crossing rates, state time duration, and analytical BER for coherent and non-coherent PSK and FSK schemes are derived and plotted.

3. Adaptive modulation and coding

The objective of AMC is to maximize data rate by adjusting transmission parameters to the available CSI, while maintaining a prescribed PER, P_0. Let N denote the total number of available transmission modes. We assume constant power transmission, and partition the entire SNR range into $(N+1)$ non-overlapping consecutive intervals with boundary points denoted as $\{\gamma_n\}_{n=0}^{N+1}$. Specifically, mode n is chosen when $\gamma \in (\gamma_n, \gamma_{n+1})$.

Channel quality can be captured by a SNR (γ) parameter. Since the channel varies from frame to frame, the Nakagami-q (Hoyt) model is adopted to describe SNR statistically. Nakagami-q (Hoyt) fading channel is considered because this is typically observed on satellite links subject to strong ionospheric scintillation and can also be used to describe multipath propagation in heavily shadowed environments. The Nakagami-q fading parameter (q ranges from 0 to 1) with $q=0$ corresponding to one-sided Gaussian fading, and $q=1$ corresponding to Rayleigh fading. The received SNR per frame is a random variable with Nakagami-q PDF given as [22]

$$p_\gamma(\gamma) = \left(\frac{1+q^2}{2\Omega}\right)\gamma\,\exp\left(-\frac{(1+q^2)^2}{4\Omega}\right) I_0\left(\gamma^2\frac{1-q^4}{4q^2\Omega}\right) \quad \forall\gamma > 0, \tag{1}$$

where q is the Hoyt parameter, Ω is the average received SNR, γ is the received instantaneous SNR, and $I_0(\cdot)$ is the modified Bessel function of order 0.

To avoid deep channel fades, no data is sent when $\gamma_0 \le \gamma < \gamma_1$, which corresponds to the mode $n=0$ with rate $R_0=0$. The design objective for AMC is to determine the boundary points, $\{\gamma_n\}_{n=0}^{N+1}$. The approximate PER in the presence of additive white Gaussian noise (AWGN) can be expressed as

$$\mathrm{PER}_n = \begin{cases} 1, \text{if} \quad 0 < \gamma < \gamma_{p_n} \\ a_n \exp(-g_n), \text{if} \quad \gamma \ge \gamma_{p_n} \end{cases}, \tag{2}$$