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Performance analysis of IEEE 802.11 WLANs with rate adaptation in time-varying fading channels

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ABSTRACT

The IEEE 802.11 supports multiple transmission bit rates by using different modulation and coding schemes. Due to different bit error characteristics and transmission efficiencies of the rates, stations may benefit from an adaptive use of them for a varying channel condition, called *rate adaptation*. The accuracy of rate adaptation is expected to be highly affected by a time varying nature of typical radio channels due to multipath fading. This paper presents an analytic model of the IEEE distributed coordination function (DCF) with the automatic rate fallback (ARF) rate adaptation algorithm, which is the most widely used one in the 802.11 market, under time-correlated Rayleigh fading. The key idea behind the approach is to exploit the first-order Markovian approximation of Rayleigh fading channels, based on which transmission failure probabilities are obtained depending on the current and previous transmission status. By using those probabilities, the ARF process of a station is modeled as a Markov chain, then, the rate distribution obtained by solving the Markov chain is fed to a DCF model. The proposed DCF model is described in a per-station manner, thus enables the analysis of heterogeneous channel conditions and medium access control (MAC) configurations among stations.

1. Introduction

The physical layer (PHY) of the IEEE 802.11 supports multiple transmission rates by using different modulation and coding schemes, e.g. four rates in the 802.11b (1, 2, 5.5 and 11 Mbps) [1]. Since the PHY rates have individual bit error characteristics, there usually exists a single best rate in a given channel condition, which maximizes the throughput performance. Therefore, wireless stations are encouraged to perform *rate adaptation* by which each station adaptively selects the best PHY rate depending on its channel quality. To achieve this goal, a rate adaptation algorithm needs to specify two basic mechanisms: (1) how to estimate the current channel quality; (2) when and how to change the rate [2]. Although rate adaptation is unspecified by the 802.11 standards, it plays a critical role with respect to the system performance of 802.11 WLANs [3] and thus it is of crucial importance.

The automatic rate fallback (ARF) algorithm [4] is a simple rate adaptation algorithm, which was originally developed for Lucent Technologies' WaveLAN-II WLAN devices. ARF estimates a channel quality based on the results of the past transmission attempts, i.e., a certain number of consecutive transmission successes (failures) infer an improved (degraded) channel quality. According to the estimated channel quality, it changes the rate to the next higher or next lower one. Due to its simple behavior and wide acceptance in the market, ARF became the basis of many other proposals for rate adaptation algorithms [2,5–12].

It is well known that a channel quality may fluctuate due to a varying received signal strength over a short period of time or short travel distance, which is called *small-scale fading* [13]. Small-scale fading is caused by interference between two or more versions of the

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transmitted signal, called *multipath waves* which traverse different paths. If a transmitting/receiving station or surrounding objects are in motion, they induce a Doppler shift on those multipath waves, and consequently, the received signal strength becomes time varying. Time-correlation of such a time varying channel identifies how fast the channel response changes, and is directly impacted by the Doppler shift (large Doppler shift corresponds to low correlation). The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a signal under small-scale fading [13].

Such a time varying nature of small-scale fading is closely related to the reactive behavior of rate adaptation algorithms. Especially, when a rate adaptation algorithm exploits the past statistics of channel estimation results (e.g. ARF), the accuracy of its decision making will be affected by the time-correlation of fading channels. Therefore, it is of crucial importance to take into account small-scale fading when evaluating the performance of rate adaptation in WLANs.

1.1. Previous work

The IEEE 802.11 standard defines a mandatory medium access control (MAC) scheme, called the distributed coordination function (DCF). DCF can provision best-effort service efficiently with simple behaviors based on carrier sense multiple access with collision avoidance (CSMA/CA) and thus most of today's WLAN devices implement DCF only.

There have been many researches to model the IEEE 802.11 DCF under a single PHY rate, extended from the Markov chain model introduced by Bianchi [14]. Ziouva and Antonakopoulos [15] developed a delay model. Maximum retransmission count was considered in [16,17]. The prioritized channel access scheme, specified by the 802.11e standard for supporting quality of service (QoS) [18], was considered in [19–21]. Some work considered an error-prone channel where independent channel errors are randomly generated [22–24]. A non-saturation traffic condition was considered by some recent work [25–30].

The case of multiple PHY rates was analytically modeled by Yang et al. [20] with the restriction that stations are assigned fixed PHY rates (e.g. half of stations use 11 Mbps while the other half use 5.5 Mbps). The Yang et al.'s model successfully captured the performance anomaly problem of multi-rate WLANs where the overall performance is severely degraded due to low-rate stations [31]. However, it neither considers a rate adaptation algorithm for determining stations' PHY rates nor channel errors.

In [32], the author proposed a model considering the ARF algorithm in an independent additive white gaussian noise (AWGN) channel. The proposed model uses a two-step approach where the ARF algorithm and the DCF mechanism are separately modeled and then the rate distribution obtained from the ARF model is fed to the DCF model. Such an approach simplifies the overall model and reduces its complexity. Choi et al. [33] developed an ARF model in conjunction with the transmission control protocol (TCP) in an independent error-prone channel.

Although there have been a few attempts to model ARF as mentioned above, they considered neither fading channels nor correlated channel errors. Knowing that one of the important design points of a rate adaptation algorithm is how accurately it reacts to a varying channel condition, it is essential to consider time varying fading channels in the modeling of rate adaptation.

1.2. New contribution

This paper presents a new mathematical model of the ARF rate adaptation algorithm with the IEEE 802.11 DCF under a saturation traffic condition in time-correlated Rayleigh fading channels. The key idea for making the model tractable is to exploit the first-order Markovian approximation of Rayleigh fading channels, which has gained some acceptance in the literature (described in more detail in Section 2), where the probability density function (pdf) of a channel condition at a given moment depends only on the very previous channel condition. To the best of the author's knowledge, this is the first attempt to analyze 802.11 WLANs with the ARF algorithm in time-correlated Rayleigh fading channels.

The contribution of this paper pertains to these new aspects:

- The proposed model considers time-correlated Rayleigh fading channels. Based on the first-order Markovian approximation of Rayleigh fading channels, transmission failure probabilities are obtained depending on the current and previous transmission status. By using those probabilities, the ARF process of a station is modeled as a Markov chain, which fully describes counter manipulation and rate control of the ARF algorithm. Then, the probability distribution among multiple PHY rates obtained by solving the Markov chain is fed to a DCF model. That is, the proposed model utilizes the two-step approach framework of the author's previous model so that it also has an analogous benefit, i.e., simplicity.
- The proposed model considers heterogeneous conditions among stations, contrary to the previous models considering only identical conditions among stations. The heterogeneous conditions considered in this paper include channel conditions (e.g. path loss, Doppler shift) and MAC configurations (e.g. ARF turn-on/off, Request-To-Send (RTS)/Clear-To-Send (CTS) exchange turn-on/off). This is achieved by modeling DCF in a per-station manner while the previous models concerned with multi-rate [20,32,33] are based on a per-rate manner.
- The effect of Rayleigh fading channels on the ARF behavior is studied through ns-2 simulation, compared to the case of AWGN channels. Numerical results show that Rayleigh fading highly affects the system performance and rate distribution, and the proposed model can accurately predict it. It is also shown that Rayleigh fading and AWGN channels have different optimal parameter settings of ARF at a given condition.