Int. J. Electron. Commun. (AEÜ) 64 (2010) 1031–1041

Contents lists available at ScienceDirect

Int. J. Electron. Commun. (AEÜ)

journal homepage: www.elsevier.de/aeue

Throughput behavior of link adaptive 802.11 DCF with MUD capable access node [☆]

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ARTICLE INFO

Article history:
Received 24 July 2008
Accepted 22 September 2009

Keywords:
Multi-packet reception
802.11 Media Acess Control
Carrier sense multiple access
Markov chain analysis
Distributed coordination function

ABSTRACT

Conventional IEEE 802.11 medium access control (MAC) protocol discourages simultaneous transmission to avoid collisions. With fast advances in physical layer technologies, multi-user detection (MUD) capable receivers which can detect multiple frames from different users simultaneously become available. If we are to utilize them in today's wireless LAN, however, it is not entirely clear how we should change the MAC and how much benefit is available and can be obtained by doing so. The primary objective of this paper is to investigate such questions. We approach this objective by developing a new throughput expression for 802.11 distributed coordination function (DCF). The derived expression has been verified in simulation. We show that significant throughput gain can be garnered with slight modification in 802.11 DCF.

1. Introduction

The single packet reception constraint at the access node in conventional wireless multiple access networks can be relaxed using multi-user detection (MUD) techniques which can decode information transmitted from multiple stations simultaneously. In the past, a MUD receiver [1] was viewed as an exclusive technique, perhaps deemed suitable only for high performance base stations in cellular networks, as high complexity operations were usually required for it. Recent advances in the graph code theory such as low-density parity-check codes and interleaved convolutional codes have made MUD less computationally intensive via the use of turbo-iterative algorithms, see [2–5]. Users can be differentiated by channel codes. This user separation via channel code alone has received attention in the past and proven to be more spectrum efficient than what the conventional approach of separated spreading and channel coding can provide [6].

The downside of such MUD receivers is that the receiver complexity still increases, at least linearly to the number of users. Therefore, for an access node in a typical Wireless Local Area Network (WLAN) application, the number of users, say m, that a MUD receiver can detect simultaneously will likely be limited up to several signals at maximum. We will call such an access network m-MUD enabled.

We are interested in examining the throughput behavior of a WLAN when the access node is m-MUD enabled. We aim to achieve this goal by deriving a new throughput expression.

With employment of an m-MUD enabled access node, lesser collision and thus increased effective information transmission is expected as more than one stations can transmit successfully to the access node simultaneously [7]. With the employment of a centrally controlled MAC protocol, such as the point coordination function in 802.11, polling of stations can be used and exactly m stations can be scheduled to access the channel simultaneously. This case is not of interest in this paper.

We are interested in a distributive MAC and thus aim to analyze the distributed coordination function (DCF) [8] in 802.11. The basic access mechanism used in 802.11 MAC protocol is carrier sense multiple access with collision avoidance (CSMA/CA). Stations are not allowed to send frames whenever they sense signaling activity in the channel. On top of CSMA/CA, stations follow the distributed coordination function (DCF) with which they share the medium while avoiding collision via randomized transmissions. In the standard 802.11 MAC, simultaneous transmissions from multiple stations to the access node is considered as collision and hence discouraged. The control is done by

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doi:10.1016/j.aeue.2009.10.007

providing each station with a prescribed contention window (CW) size. For m-MUD enabled 802.11 DCF, we need to encourage simultaneous transmissions up to a certain level. One can achieve this objective by decreasing the size of CW. But what sizes of CWs we should allow the stations to use vary for different m and for different groups where users in different group uses different transmission rate via link adaptation (see next paragraph for more explanation). Our throughput expression can be used to evaluate this problem and provide a solution.

The throughput expression in this paper, therefore, is derived under the assumption that each station in the network employs link adaptation [9,10]. With link adaptation, stations choose a data rate depending on underlying channel condition. As the signal to noise ratio (SNR) available to a station increases, it uses higher data rates to transmit its frame, hence reaching closer to channel capacity. Link adaptation in WLAN changes the throughput behavior of WLAN significantly [11,12]. Thus, it is meaningful to include link adaptation in our analysis and see its impact on the throughput behavior.

The contributions of this paper are therefore as follows: first, we derive the throughput expression for the multi-rate 802.11 MAC protocol with the support of MUD capable access node. To the best of our knowledge, this is novel (see our comparative literature analysis in the next section). Second, we show how this throughput expression can be used in the optimal control of 802.11 DCF.

The rest of the paper is organized as follows. In Section 2, we provide comparison of this work to prior works. In Section 3, we describe the system model of our m-MUD proposed WLAN. The backoff process of 802.11 is then modeled as a Markov chain. Analytical framework to investigate network throughput is presented in Section 4. Section 5 contains numerical results and their comparison with simulations. Performance enhancement mechanisms and MAC protocol that may be employed to get the maximum advantage of MUD capability are discussed in Section 6, following which we conclude.

2. Comparison to prior work

Many works exist in the literature, which analyzed the network throughput of IEEE 802.11. Bianchi [13,8] modeled 802.11 DCF using Markov chains and evaluated the performance of WLANs using single transmission rate. Improvements were then presented by several researchers which include the details of 802.11 DCF in the Markov chain model for performance analysis. It should be pointed out that while substantial research is conducted on throughput analysis assuming single data rate, not comparable attention is given to the scenario where stations are allowed to use different data transmission rates, a typical case in modern 802.11 WLANs.

More recently conducted researches reported in [11,14–16] accommodate multi-rate transmission. Yang et al. [11], assume exponential backoff procedure, as outlined in the IEEE 802.11 DCF. The model, an improved version of the one presented in [8], accommodates multi-rate transmission. With employment of multi-rate transmissions, "performance anomaly" problem was observed: low rate users hold the channel longer in time and thus the overall network throughput suffers. The authors have tried to address this problem by controlling access parameters of stations such as the initial contention window size, the frame size, and the maximum backoff stage. All these parameters are well defined in the IEEE 802.11 standard. This problem of performance anomaly was also observed in [16]. In [15], the authors analyze multi-rate 802.11 WLANs, where they assume two Markov chain models for stations and channels. However, the remedial solution for the performance anomaly was not addressed.

The authors in [17] attempted to apply a MUD capable access node in IEEE 802.11 WLANs and proposed a modified MAC. They assumed a simple scenario in which all nodes have the same SNR and use geometrically distributed random backoff interval as compared to the exponential backoff in DCF. In [18,7], the authors attempted to implement multiple packet reception (MPR) in 802.11 WLANs using DCF. CSMA was modified for MPR scenario in [12] and a modified cross layer CSMA for MPR, named XL-CSMA was proposed. Although decentralized, it did not assume DCF mechanism for backoff. We point out that these prior works with 802.11 and MUD mentioned here assume single transmission rate for throughput analysis.

In [19], the authors have addressed the throughput unfairness problem for a network of spatially distributed nodes. Distant nodes due to poor channel conditions suffer from low throughput. This is in fact the same phenomenon observed in [17]. There they aim to increase the overall throughput. Here the point is fairness. To enhance the throughput of distant nodes, the authors of [19] proposed a simple modification in a MAC with which a node selects a transmission probability from two possible values – high and low. A station with an unsuccessful transmission history is allowed to select the high transmission probability.

The works compared so far in this section start with the assumption of the classic CSMA/CA framework where simultaneous transmissions are discouraged. Among the earlier works on multi-packet reception (MPR) in random access networks, the authors of the paper [20] studied slotted ALOHA (SA) systems under infinite number of users and single buffer assumption. Stations under SA transmit at the start of each frame whenever they have a frame to send. Thus, simultaneous transmission is easier than under CSMA/CA to be encouraged via manipulating the transmission probabilities. However, there are downsides as well which make SA less attractive than 802.11. The throughput of SA is poor. For example, the throughput is only compared to the offered load (for single user detection receivers); the throughput vanishes as the offered load increases. SA is known to have instability problem as the offered load increases requiring a separate remedial treatment [20]. Furthermore, most of the existing MPR MAC protocols [20,21], assume the existence of a central coordinator that schedules transmissions from stations. Hence, these prior works are not applicable to our 802.11-based distributed approach here.

To the best of our knowledge, this paper provides the first work which attempts to analyze multi-user detection (MUD) in a multi-rate 802.11 *WLANs in which stations use DCF to enter into exponential backoff before transmitting their frames.*

3. System model for multi-rate 802.11 m-MUD

3.1. System description

Fig. 1 depicts a basic service set (BSS) system in consideration. All the stations in the BSS are divided into N groups; those belonging to each group transmit their frames at the data rate of r_i for $i = 1, 2, \ldots, N$. It is further assumed that there are a total of M stations in the network, each group having M_i number of stations having their frames ready to be transmitted, i.e. $M := \sum_{i=1}^{N} M_i$. There are n_i stations from the i th group which start their transmission simultaneously at the start of the same timeslot. Hence, overall, there are n number of stations starting transmission simultaneously, where $n := \sum_{i=1}^{N} n_i$.