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Performance study of block ACK and reverse direction in IEEE 802.11n using a Markov chain model

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A B S T R A C T

IEEE 802.11n networks are widely used in home and corporate network environments because they offer high-speed wireless Internet access at relatively low-cost. The 802.11n standard introduced several key features including Block acknowledgement (ACK) and reverse direction (RD) data transmission for enhanced system performance. An in-depth study of 802.11n system capacity for Block ACK mechanisms (both protected and unprotected) and RD data flows is required to assist optimum planning and design of such systems in view of the limited wireless channel capacity. In this paper we study the interdependencies of Block ACK and RD mechanisms using a discrete bi-directional Markov chain model under non-saturated traffic loads. We present a mathematical model to derive throughput, delay, and packet loss probability for both protected and unprotected Block ACKs under varying loads. We validate the model using MATLAB based numerical studies. Results obtained show that the combined effect of protected Block ACK and RD flows has a positive impact on system performance. However, unprotected Block ACK wastes transmission opportunity (TXOP) especially in collisions and therefore degrades the system performance. Our findings reported in this paper provide some insights into the performance of 802.11n with respect to Block ACK and RD methods. This study may help network researchers and engineers in their contribution to the development of next generation wireless LANs such as IEEE 802.11ac.

1. Introduction

IEEE 802.11-based wireless local area networks (WLANs) are widely adopted in home and corporate networking environments due to their simplicity in operation, robustness, low cost, well-defined standards (e.g. 802.11a/b/g/n) and the user mobility offered by the technology. In the 802.11 standard, the distributed coordination function (DCF) is defined as a mandatory medium access control (MAC) protocol and the point coordination function (PCF) is optional (Standards Committee, 2005). The performance of DCF has been analyzed extensively using mathematical modeling and simulation (Bianchi, 2000; Daneshgaran et al., 2008; Lee et al., 2007; Ahuja et al., 2013; Kosek-Szott, 2014). Bianchi (2000) proposed a Markov chain model for a backoff mechanism to evaluate the throughput under saturated traffic and error free channel condition. Bianchi's work assume that packets will eventually be transmitted regardless of the no. of retransmissions. However, a station (STA) will increase its contention window size after each failed transmission until it reaches the maximum backoff stage. Since the maximum backoff stage and retry limit are not equal, the contention window size remains the same and STA will continue retransmitting until it reaches a retry limit. If the subsequent transmission is not successful, the packet is discarded. The authors in Wu et al. (2002), developed a Markov model which considers a finite retry limit for the transmission control protocol (TCP) over WLANs. They considered saturated traffic loads under ideal channel conditions. The extension of Bianchi's model was reported in Alizadeh-Shabdiz and Subramaniam (2003) for finite load analysis. However, the maximum capacity of a wireless node is bounded by queue delays (Liaw et al., 2005). A finite load Markov model is presented in Liaw et al. (2005) by integrating a queue model as a new state with a Bianchi model assuming the STA queue is empty after successful transmission. All of these models are well studied for 802.11(a/b/g) networks. The fundamental goal of these models is to study the DCF protocol behavior under different channel and load conditions. The common thread of these studies is that the system performance can be enhanced by reducing MAC overheads.

The 802.11e standard (Standards Committee, 2005) published in 2005, proposed a new MAC method called hybrid access method (HCF). A new ACK scheme is being introduced in the 802.11e standard known as BA. Unlike the traditional ACK scheme, an ACK is trans-

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mitted to reply to multiple data frames rather than per frame as in BA. Hence, the Markov model that has been developed for the traditional DCF protocol does not fit well with the BA scheme used to investigate the system throughput performance. Authors in Li et al. (2005) developed a Markov model for the BA and showed that a block with multiple frames can offer higher throughput than the traditional ACK based two-way or four-way transmission under saturated load and infinite retransmission conditions. However, when the frame consists of only one data frame it suffers from severe throughput degradation due to a couple of additional frames (e.g. BA request and BA). Moreover, it is assumed that data frames received with errors are considered a successful transmission, thus the contention window is reset. Unfortunately, according to the standard, receivers will not acknowledge the error data frame. Consequently, the sender has to retransmit the frame and increase the contention window if it does not reach a maximum contention value. Further enhancement of Li et al. (2005) is reported in Lee et al. (2007) by introducing a protected BA mechanism. The work reported in Lee et al. (2007) inspired by further extensions of finite load conditions and integrating the RD features of 802.11n. An extension of basic Block ACK schemes in IEEE 802.11e was introduced in Arif and Sari (2012) to investigate the throughput performance produced by using A-MSDU and compressed Block ACK scheme. Beside the BA scheme, a frame aggregation mechanism is widely studied in recent literature to enhance the performance of 802.11n networks. In Kim et al. (2008) discrete time Markov chain model is used to analyse the post backoff behavior due to frame aggregation under an error free environment. The performance study shows that, MAC service data unit (MSDU) outperforms the MAC protocol data unit (MPDU) as frame aggregation size becomes larger. An empirical study performs in Visoottiviseth et al. (2009) also confirms that a significant performance enhancement can be achieved when the frame aggregation and BA schemes are utilized. However, under an error prone channel frame aggregation mechanism experience severe throughput degradation and higher access delay due subframes size (Hajlaoui et al., 2013). To examine the effects of frame aggregation and Block ACK, an analytical model is developed in Frohn et al. (2011) for IEEE 802.11n based mesh networks. It modeled the throughput at MAC layer as a function of physical data rate, error rate, aggregation level and path length. So far, we only consider the unidirectional data transmission. A bi-dimensional Markovian model presented in Mohammad and Muhammad (2012) shows that, bi-directional data transmission significantly enhance the overall network performance. An accurate two dimensional Markov Chain model for 802.11n has been studied in Hajlaoui et al. (2016) to investigate the throughput performance when frame aggregation and Block ACK schemes are adopted. However, frame aggregation improves the access point saturation throughput at the cost of the a performance degradation for conventional nodes connected to the AP (Soleymani et al., 2016). Further study on frame aggregation is presented in Karmakar et al. (2016) by introducing an additional dimension with the existing Bianchi Markov model. The third dimension is used to analyse the effect of frame aggregation. It only considered the protected Block ACK mechanism. Most of the previous studies on performance enhancement of 802.11n have focused on frame aggregation mechanisms. Very limited studies have actually analyzed the throughput performance of 802.11n under non-ideal channel conditions incorporating both Block ACK and RD mechanism. Moreover, it is essential to study the impact of protected and non-protected Block ACK schemes in 802.11n performance. Therefore, this research developed an analytical model to track and trace the performance fluctuation issues of 802.11n networks using Markov Chains.

The main contribution of this paper is three fold. First, we present a simple Markov model to study the performance of 802.11n standard under non-saturated traffic load. A detailed Markov chain model is developed by considering all possible constrains including load conditions, retry limits and channel state information. Second, we derived both Throughput and Packet delay for both the protected BA and non-protected BA schemes. Third, the effect of load conditions is analyzed in terms of packet loss probability. Moreover, an extensive MATLAB based numerical studies is presented to validate analytical model.

The rest of the paper is organized as follows: We describe the BA and RD mechanisms in Section 2. Section 3 presents a detailed discrete Markov model for 802.11n with a protected BA mechanism followed by three different subsections throughput, packet delay probability and mean delay (including MAC delay and Queue delay in consecutive subsections) analysis. A detailed numerical study including a comparative study of various mechanisms is presented in Section 4. A brief discussion in Section 5 ends the paper.

2. Preliminaries

2.1. Block ACK mechanism

The Block ACK mechanism was first introduced in Standards Committee (2005) to reduce the MAC overhead of 802.11e and later in 802.11n. The basic idea of the BA mechanism is to aggregate several ACK frames into a single frame. There are two different types of Block ACK mechanisms: Immediate (Im) and Delayed (D) Block ACK. A further extension of 802.11n for High Throughput(HT) operations classifies each of these Block ACK schemes in two subclasses: Protected and non-protected Block ACKs. The scope of this paper is limited to the Im-Block ACK scheme for both protected and non-Protected modes. In the Im-Block ACK scheme, transmitters and receivers are known as originators and recipients, respectively. To initialize the new acknowledgement policy, the originator and the recipient will exchange Add Block Acknowledgement (ADDBA) Request/Response frames. Afterwards, a data block with multiple data frames is transmitted from the originator to the recipient with Block ACK Request (BAR) at the end. The number of data frames in one data block is bounded by the receiver buffer size. The recipient sends a Block Acknowledgement (BA) frame for the entire data block. Fig. 1(a) shows the protected Block ACK channel access mechanism. In protected Block ACK, before transmitting an entire data burst, the originator will transmit a single data frame and wait for an ACK from the recipient. After the successful reception of an ACK frame, the originator initiates the transmission opportunity (TXOP) period to transmit the data burst. Therefore, if there is an error or channel collision,this problem would only be

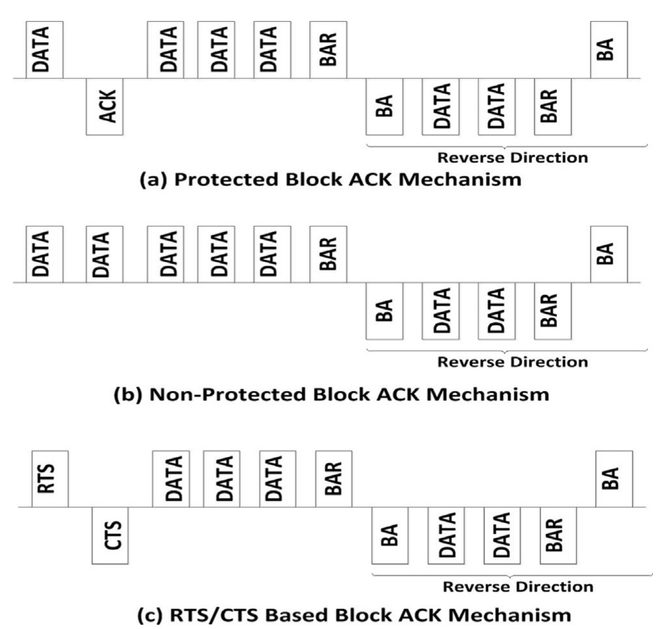

Fig. 1. Various block ACK mechanisms with reverse direction.