The Performance Study of Optimal Contention Window for IEEE 802.11 DCF Access Control

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Abstract—**The IEEE 802.11 protocol has achieved worldwide acceptance with WLANs. In order to maximize the throughput, we must spend lots of time to find out the best contention window. In this paper, we proposed a model to derive the optimal contention window to maximize the throughput for a given network scale. In addition, we analyzed the access delay of the model.**

Keywords-WLANs; Contention Window; DCF

I. INTRODUCTION

Most of consumer electronic devices have the 802.11 wireless communication capability (WiFi-enabled). In wireless local area network (WLAN) systems, the IEEE 802.11 standard has been one of the most common protocols in the world. The current most popular random access protocol used in wireless ad-hoc network is IEEE 802.11 Medium Access Control (MAC) protocol. In IEEE 802.11 standard [1], the MAC protocol technique is called Distributed Coordination Function (DCF). DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme and slotted binary exponential backoff algorithms. There have been many performance analyses [2-8] of the IEEE 802.11 DCF. However, in these performance analyses, the common conclusion is that although the DCF scheme is not difficult to implement, and its performance is sub-optimal, as it has several attempts to find out approximately the best contention window (CW).

The rest of this paper is organized as follows. An overview of IEEE 802.11 DCF is depicted in Section II. The detail description of the model we proposed is depicted in the Section III. The performance analysis is depicted in the Section IV. The simulation results are shown in Section V. Finally, Section VI gives the conclusions.

II. OVERVIEW OF IEEE 802.11 DCF

In the IEEE 802.11 DCF MAC protocol, the channel is shared by competing stations. In the protocol, if a station detects the channel being busy as it has a frame to send, the station shall defer a random backoff time until the channel is sensed idle. The backoff timer is then starts decrementing once per slot time after the channel becomes idle. The timer will be stopped when the channel is sensed busy again and then continue after the channel remain idle for a DCF Inter-frame Space (DIFS) time. The station starts to transmit its frame when the backoff counter reaches zero. At each transmission, the station sets its backoff timer to a random number uniformly distributed over the interval $(0, W\text{-}1)$ where W is the current contention window size. The CW is dependent on the number of unsuccessful transmissions for the frame. At the first transmission attempt, W is set to the minimum contention window size CW_{min}. After each unsuccessful transmission, the window size is doubled until maximum window size is reached. Once it reaches maximum window size, contention window shall remain at the maximum size until reset. After the transmitted frame is successful, the station will reset its contention window to CW_{min}. If the transmitting station does not receive the ACK within a specified ACK timeout or it detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the previous backoff algorithm. The above mechanism is called the ACK mechanism.

A common problem in WLAN systems is hidden-terminal problem. The hidden-terminal problem happens when the transmissions occur simultaneous of two source stations that cannot hear each other, but are both received by the same destination station. The existence of hidden-terminal may result in performance degradation and the high probability of collision. To resolve the hidden-terminal problem, an optional four-way handshakes data transmission mechanism called request-to-send/clear-to-send (RTS/CTS) mechanism is also defined in the DCF. Before transmitting a frame, a station operating in a RTS/CTS mode "reserves" the channel by sending a special RTS short frame. The destination station acknowledges the receipt of a RTS frame by sending back a CTS frame. The RTS/CTS mechanism improves on the system performance by reducing the duration of a collision when long messages are transmitted [1].

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III. THE SYSTEM MODEL

The main concept of our system model is that all stations have the same CW interval to determine the backoff timer without the need of the traditional binary exponential backoff algorithm. That is, whenever a station wants to access the channel, it chooses a random backoff timer over the same interval (0, W-1) and then begins to perform the backoff procedure.

A. Model Description

The model we proposed is a one dimensional Markov chain as shown in Fig. 1. The new Markov chain model contains W backoff states, denoted by $0, 1, 2, \ldots, W\text{-}2$, and $W\text{-}1$.

In modified model, there is another state, denoted by −1. The backoff procedure is invoked whenever a station has a frame to transmit and finds the channel busy or whenever the transmitting station infers a failed transmission. Whenever the backoff counter is equal to zero and the station transmits without entering the backoff procedure.

In the new Markov chain model, there is no concept of retry stage. No matter the frame is transmitted successfully or not, the station will choose the new backoff timer for the new frame.

B. Frame Transmission

Before transmitting its frame, a station starts the backoff procedure by setting its backoff timer to a random number uniformly distributed over the interval (0, W-1) and then starting to decrement the counter to zero. The transmission probabilities are listed as follows:

- The backoff timer freezes when the station senses the channel is busy:

$$p\{k|k\} = p_b,\ 1 \le k \le W-1. \tag{1}$$

- The backoff timer decrements when the station senses the channel does not have any transmission:

$$p\{k|k+1\} = 1-p_b,\ 1 \le k \le W-2. \tag{2}$$

- The station transmits its frame without entering the backoff procedure if it detects that its previous transmitted frame was successfully received and the channel is idle:

$$p\{-1|-1\} = (1-p_b)(1-p_c). \tag{3}$$

- The station defers the transmission of a new frame and enter the backoff procedure:

$$p\{k|-1\} = \frac{p_b+p_c-p_bp_c}{W},\ 0 \le k \le W-1. \tag{4}$$

- The station enters the – 1 state no matter the frame is transmitted successful or not and it senses the channel idle:

$$p\{-1|0\} = 1-p_b. \tag{5}$$

- The station enters the – 1 state no matter the frame is transmitted successful or not and it senses the channel idle:

$$p\{k|0\} = p_b/W. \tag{6}$$

Let $b_k = \lim_{t\to\infty} P\{b(k)\},\ -1 \le k \le W-1,$ be the stationary distribution of the chain. Owing to the chain regularities, the following relations hold:

$$b_{-1} = \frac{1-p_b}{p_b+p_c-p_bp_c}b_0. \tag{7}$$

$$b_k = \frac{W-k}{W}\frac{1}{1-p_b}b_0,\ 1 \le k \le W-1. \tag{8}$$

The value of b_0 is determined by imposing the normalization condition:

$$b_{-1} + \sum_{k=0}^{W-1} b_k = 1. \tag{9}$$

Let τ be the probability that a station can transmit a frame. From (6) to (8), we have

$$\tau = \frac{2(1-p_b)(1+p_c-p_bp_c)}{2(1-p_b)^2+(W+1)(p_b+p_c-p_bp_c)} \tag{10}$$

In (9), b_0 depends on the probability p_b and p_c. Under an ideal channel, the probability p_b that the channel is sensed busy when a station is trying to decrement its backoff timer, note that p_b is the probability that, in a slot time, at least one of the *n-1* remaining stations transmits. Therefore,

$$p_b = 1-(1-\tau)^{n-1}. \tag{11}$$

where τ is given in (10) as a function of the only unknown p. Numerically solving (11), the value of p_b is found. Therefore, we can obtain the value of p_b.

IV. PERFORMANCE ANALYSIS OF MODIFIED MODEL

A. Throughput Analysis

Since n stations contend for accessing the channel, and each transmission with a probability τ. In order to analyze the performance of the model, the following probabilities are needed to calculate the throughput.

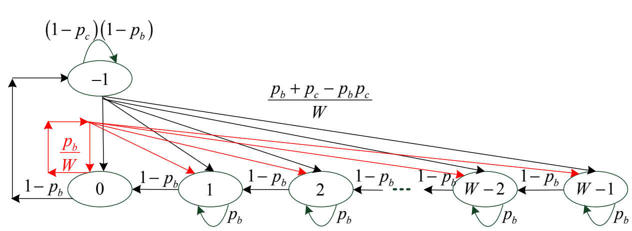

Figure 1. New Markov chain model.

Let p_i be the probability that there is no transmission:

$$p_i = (1-\tau)^n. \tag{12}$$

And p_t be defined as the probability that at least one station is transmitting. Based on (11), we get:

$$p_t = 1-(1-\tau)^n. \tag{13}$$

Let p_s be the probability that exactly one station is in the transmission state, conditioned on that at least one station is transmitting. So the conditional probability can be derived as:

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{P_t} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{14}$$

The state of the transmitted frame is either successful or failed. Hence, let p_c be the probability that the transmitted frame is failed, i.e., p_c is the probability that the transmitted frame is collided. So, the probability that the collisions occur is the complement of p_s. Therefore, we can derive p_c as

$$p_c = 1-p_s = 1-\frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{15}$$

Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload. The throughput S is expressed as

$$S = \frac{T_p p_s p_t}{\sigma \cdot p_i + (T_s p_s + T_c p_c)\, p_t}, \tag{16}$$

where T_p is the average time used to transmit the MAC frame. T_s is the average time the channel is sensed busy because of a successful transmission, and T_c is the average time the channel is sensed busy by each station during a collision. σ is the duration of an empty slot time.

To compute the throughput for a given DCF access mechanism, it is now necessary to specify the corresponding values of T_s and T_c. For IEEE 802.11 ACK mechanism, assuming T_{PHY} as the time duration of PHY header, and T_{ACK} is the time duration used to transmit an ACK frame, T_s and T_c can be expressed as

$$\begin{aligned} T_s^{ack} &= T_{PHY} + T_p + \delta + SIFS + T_{ACK} + \delta + DIFS, \\ T_c^{ack} &= T_{PHY} + T_p + \delta + DIFS, \end{aligned} \tag{17}$$

where δ is the propagation delay.

For RTS/CTS mechanism, T_s and T_c can be expressed as

$$\begin{aligned} T_s^{RTS/CTS} &= T_{RTS} + T_{CTS} + T_{PHY} + T_p + T_{ACK} + 3*SIFS + 4*\delta + DIFS, \\ T_c^{RTS/CTS} &= T_{RTS} + \delta + DIFS. \end{aligned} \tag{18}$$

Where T_{RTS} and T_{CTS} are the time duration used to transmit an RTS frame and CTS frame, respectively.

B. Access Delay Analysis

The access delay $E[D]$ is defined as the average time for a station since a station begins to contend for the channel until the contention is successful and the station begins to transmit its frame. The access delay depends on the value of the backoff timer and the duration when the counter freezes due to other transmissions. So, the average access delay for a frame to access the channel can be derived as

$$E[D] = E[X]\sigma + E[F]\cdot\left[p_{b,s}T_s + (p_b - p_{b,s})T_c\right]. \tag{19}$$

Considering that the timer of a station is at state b_k, then a time interval of k slot times is needed for the timer to reach state b_0, without taking into account the timer is stopped [9]. The average value of the backoff timer $E[X]$ can be expressed as

$$E[X] = \sum_{k=1}^{W-1} k b_k = \frac{(W^2-1)}{6(1-p_b)} b_0. \tag{20}$$

And let $E[F]$ be the average number of time slots that the backoff counter freezes. It can be expressed as

$$E[F] = \frac{E[X]}{1-p_b} p_b. \tag{21}$$

We assume that $p_{b,s}$ is the probability only one transmission conditioned on channel is sensed busy. However, the condition of channel is sensed busy is combined into (21). So, we can express the $p_{b,s}$ as

$$p_{b,s} = \frac{(n-1)\tau(1-\tau)^{n-2}}{p_b}. \tag{22}$$

And $p_{b,c}$ is the probability that a transmitted frame experiences a collision conditioned on channel is sensed busy. Similar to (15), it can be express as

$$p_{b,c} = p_b - p_{b,s}. \tag{23}$$

C. Derivation of Optimal Contention Window

Recall the (16) and reassemble it as

$$S = \frac{T_p}{T_s - T_c + \sigma \cdot \dfrac{\frac{T_c}{\sigma}\left[1-(1-\tau)^n\right] + (1-\tau)^n}{n\tau(1-\tau)^{n-1}}}. \tag{24}$$

As T_p, T_s, T_c, and σ are constants, the normalized saturated throughput S is achieved maximum when the following quantity is maximized:

$$\frac{n\tau(1-\tau)^{n-1}}{\frac{T_c}{\sigma}\left[1-(1-\tau)^n\right] + (1-\tau)^n} = \frac{n\tau(1-\tau)^{n-1}}{\frac{T_c}{\sigma} - (1-\tau)^n\left(\frac{T_c}{\sigma} - 1\right)}. \tag{25}$$

Impose the above derivative to 0 with respect to τ. After some simplifications, we can obtain the following equation:

$$\tau_{opt} \approx \frac{1}{n} \cdot \sqrt{\frac{2\sigma}{T_c}}. \tag{26}$$

To achieve maximum throughput performance, (26) is the optimal transmission probability (τ_{opt}) that each station should transmit during a slot time. Hence, we can derive the optimal contention window (W_{opt}) as

$$W_{opt} = \frac{\left(1-\tau_{opt}\right)^{n-1}\left(\frac{n\tau_{opt}\left(1-\tau_{opt}\right)^{n-1}}{1-\left(1-\tau_{opt}\right)^{n}} - Q - \tau_{opt} + \tau_{opt}\left(1-\left(1-\tau_{opt}\right)^{n-1}\right)\right)}{\tau_{opt}\left[2-\left(1-\tau_{opt}\right)^{n-1} - \frac{n\tau_{opt}\left(1-\tau_{opt}\right)^{n-1}}{1-\left(1-\tau_{opt}\right)^{n}} - Q\right]} - 1. \tag{27}$$

Where $Q = \left(1 - \frac{n\tau_{opt}\left(1-\tau_{opt}\right)^{n-1}}{1-\left(1-\tau_{opt}\right)^{n}}\right)\left(1-\left(1-\tau_{opt}\right)^{n-1}\right).$

(26) and (27) show that if we know the number of competing stations, it is easy to calculate τopt during a slot time and the Wopt. With the optimal contention window, we can get maximum throughput performance.

V. NUMERICAL RESULTS

The parameters of our analysis are as follows: Frame payload = 1024 bytes, ACK = 14 bytes, T_{PHY} = 192 *us*, SIFS = 10 *us*, DIFS = 50 *us*, propagation delay = 1 *us* and slot time = 20 *us*.

Fig. 2 and Fig. 3 depict the saturation throughput performance using ACK mechanism and RTS/CTS mechanism, respectively. From the results, we can know that using RTS/CTS mechanism can achieve the higher maximum throughput and the CW is smaller than that using ACK mechanism. It is because that RTS/CTS mechanism can reduce the probability of collision. Therefore, with RTS/CTS mechanism can achieve the higher maximum throughput.

Fig. 4 and Fig. 5 depict the access delay performance using ACK mechanism and RTS/CTS mechanism, respectively. The access delay with RTS/CTS mechanism is smaller than that with ACK mechanism. With RTS/CTS mechanism, we can reduce the duration that the stations must wait before accessing the channel.

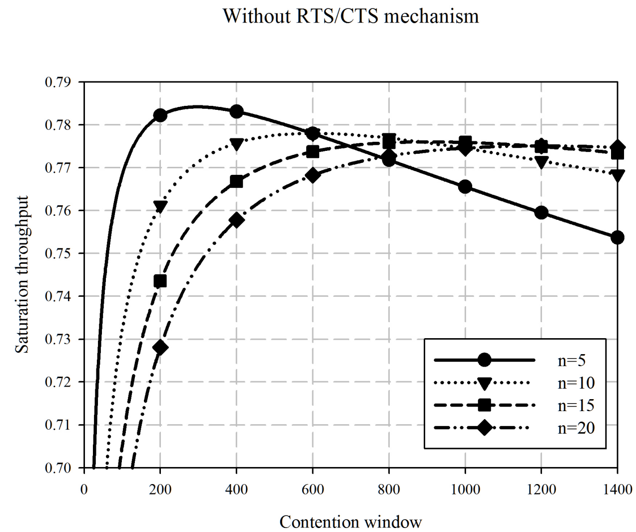

Figure 2. The normalized saturatuon throughput using ACK mechanism.

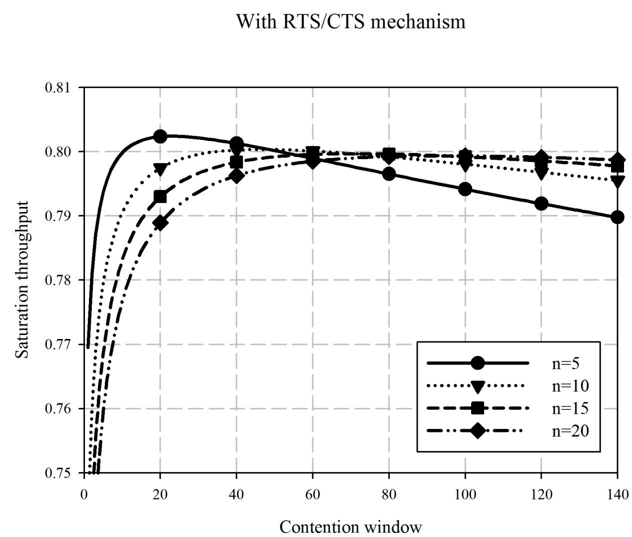

Figure 3. The normalized saturation throughput using RTS/CTS mechanism.

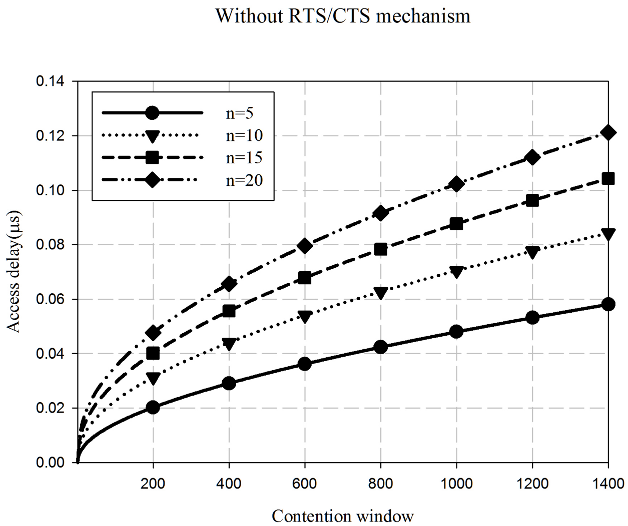

Figure 4. The access delay using ACK mechanism.

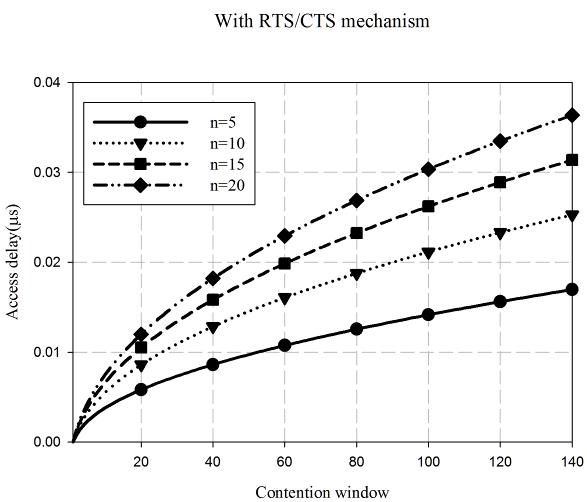

Figure 5. The access delay using RTS/CTS mechanism.

VI. CONCLUSION

IEEE 802.11 standard is widely used in wireless network. In this paper, we can derive the optimal contention window interval based on the network states information. In addition, we showed the access delay of our model. With the RTS/CTS mechanism, the duration of a collision can be reduced. Therefore, RTS/CTS mechanism can achieve higher throughput and smaller access delay than ACK mechanism.

In the future study, in order to reflect the real operation under the real channel condition, we will pay attention to the error frame occurring due to the channel fading and/or noise (channel error conditions).

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