Performance Analysis and Optimization of IEEE 802.11 DCF with Constant Contention Window

Ruopeng Wang, Jie Zhang, Xiangyi Zou
School of Electrical and Information, Northwestern Polytechnical University,Xi'an,710072,China
roro_wang200020@hotmail.com,39715322@qq.com

Abstract

In this paper, a novel MAC protocol, DCF with constant contention window (DCF/CCW), is proposed for IEEE802.11 WLANs. Firstly a mathematical model is presented to analyse the throughput and access delay of DCF/CCW. The analysis shows that the performance of DCF/CCW differs much with different network scales. And a further analysis shows it is easily to obtain the optimal CCW for a given network scale in order to maximize the system throughput. The proposed optimization mechanism, optimal-DCF/CCW, is just based on this knowledge to select optimal CCWs for different network scales. Simulation results show that compare with IEEE 802.11 DCF, optimal-DCF/CCW makes a significant improvement of throughput and access delay.

1. Introduction

In the popular and widely used IEEE802.11 standard for WLANs [1], the primary MAC 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 (BEB) rules. Since the introduction of IEEE802.11 protocols, many literatures have been proposed to analyze the performance of DCF [2]-[7]. Their common conclusion is that although the DCF scheme is simple to implement, its performance is sub-optimal, as it needs several attempts to find approximately the best contention window, and its optimal contention window is reduced to the PHY-based minimal contention window whenever the transmission is successful.

The paper is organized as follows. In section **2.** we give a general description of DCF, which is useful in understanding DCF/CCW. In section **3.** the throughput and access delay of DCF/CCW is analyzed under a proposed model. The detailed description of optimal-DCF/CCW in IEEE802.11 WLANs is depicted in section IV. And computer simulation to validate the performance of optimal-DCF/CCW is shown in section **5.** Section **6.** provides the concluding remarks.

2. Description of IEEE802.11 DCF

We will briefly introduce DCF mechanism which is useful for understanding our analytical model. Readers can refer to [1] for details.

In DCF, a station with a frame to transmit monitors the channel activities until an idle period equal to a distributed inter-frame space (DIFS) is detected. After sensing an idle DIFS, the station waits for a random backoff interval before transmitting. The backoff time counter is decremented in terms of slot time as long as the channel is sensed idle. The counter is stopped when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The station transmits its frame when the backoff time reaches zero. At each transmission, the backoff time is uniformly chosen in the range (0, $CW-1$), where CW is the current backoff window size. At the very first transmission attempt, CW equals the minimum backoff window size CWmin. After each unsuccessful transmission, CW is doubled until a maximum backoff window size value is reached

$$CW_{\max} = 2^m \times CW_{\min} \tag{1}$$

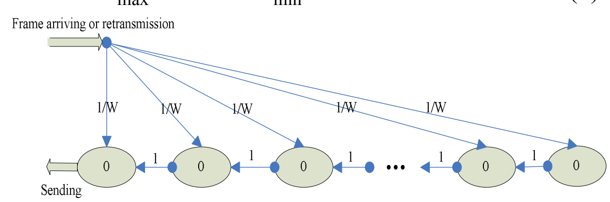

Fig.1 Markov Chain for the Backoff Window Size

transmits an acknowledgment frame (ACK) following a short inter-frame space (SIFS) time. 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 rules. Until the transmission time reaches the retry limit r, this frame is discarded.

3. Performance Analysis of DCF/CCW

Unlike the traditional DCF protocol, the main idea of DCF/CCW is to directly give the station a contention window without the need of repeated collisions in BEB. When a frame arrives, the station chooses a backoff slots from (0, CWW-1) and then begin the backoff procedure. If a collision happens, the station only needs to randomly

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choose another backoff slots from (0, *CCW*-1) to retransmit the former packet. In this section we analyse the performance of DCF/CCW for different network scales with different contention windows. Here we use *W* as the value of *CCW* for convenience in case no confusion exists.

3.1. Frame Transmission Probability

Consider a fixed number of competing terminals in saturation condition. Each station always has a frame available for transmission, and each frame needs to wait for a random backoff time before transmitting. Let *b(t)* be the stochastic process representing the backoff time counter for a given station. A discrete and integer time scale is adopted: *t* and *t*+1 corresponding to the beginning of the two consecutive slot times, and the backoff time counter of each station decrements at the beginning of each slot time. Note that this discrete time scale does not directly relates to the system time. In fact, the backoff time decrement is stopped when the channel is sensed busy, and thus the time interval between two consecutive slot time beginnings may be much longer than the slot time σ, as it may include a frame transmission.

In DCF/CCW, there is no concept of backoff stage. Each station always has the same contention window, and the value of the backoff counter of each station does not relate to its transmission history. So the stochastic process *b(t)* is Markov Chain, which is depicted in Fig.1.

No matter the frame is just arriving or retransmitted, the backoff slot is always randomly selected form (0, *W*-1). That is to say, the retry limit has only the effect to determine when to discard a frame but no influence on the Markov Chain model. The only one-step transition probabilities are

$$\begin{cases} P\{b(t+1)=k \mid b(t)=k+1\}=1 & k\in(0,W-2) \\ P\{b(t+1)=k \mid b(t)=0\}=1/W & k\in(0,W-1) \end{cases} \tag{2}$$

The first equation in (2) accounts for the fact that, at the beginning of each slot time, the backoff time is decremented. The second equation accounts for the fact that, no matter it is a new arriving frame or not, the transmission starts with a backoff slot uniformly chosen in the range (0, *W*-1). Let

$$b_k=\lim_{t\to\infty}P\{b(t)=k\},k\in(0,W-1) \tag{3}$$

be the stationary distribution of the chain. Note that

$$b_k=\frac{W-k}{W}b_0,k\in(0,W-1) \tag{4}$$

In equation (4), all values of b_k are expressed as function of the value b_0. Thus it is not difficult to obtain

$$1=\sum_{k=0}^{W-1}b_k=\sum_{k=0}^{W-1}b_0\cdot\frac{W-k}{W}=b_0\sum_{k=0}^{W-1}(1-\frac{k}{W})$$
$$=b_0\cdot\frac{W+1}{2} \tag{5}$$

As any transmission occurs when the backoff time counter is equal to zero, we can now express the probability that a station transmits in a randomly chosen slot time as

$$\tau=b_0=\frac{2}{W+1} \tag{6}$$

3.2. Throughput Analysis

In order to analyze the performance of constant contention window in DCF, let us firstly analyze what happens in a randomly chosen slot time. Let P_i be the probability that there is no transmission in the considered slot time. Since *n* stations contend for the channel, and each transmits with a probability *τ*, then

$$P_i=(1-\tau)^n \tag{7}$$

Let P_{tr} be the probability that there is at least one transmission in the considered slot time. Based on equation (7), we get

$$P_{tr}=1-(1-\tau)^n \tag{8}$$

The probability that a transmission occurring on the channel is successful is given by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits, i.e.

$$P_s=\frac{n\tau(1-\tau)^{n-1}}{P_{tr}}=\frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}h \tag{9}$$

Then the probability that a transmission occurring on the channel is not successful (collided) is

$$P_c=1-P_s=\frac{1-(1-\tau)^n-n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{10}$$

Let *S* be the normalized system throughput, defied as the fraction of time the channel is used to successfully transmit MAC frame. We are now able to express *S* as the ration

$$S=\frac{T_p\cdot P_s\cdot P_t}{T_s\cdot P_s\cdot P_t+T_c\cdot P_c\cdot P_t+\sigma\cdot P_i} \tag{11}$$

Here T_s is the average time the channel is sensed busy because of a successful transmission, T_c is the average time the channel is sensed busy by each station during a collision, and T_p is the average time used to transmit the MAC frame during a successful transmission. *σ* is the duration of an empty slot time. Note that the above throughput expression has been obtained without the need to specify the access mechanism employed. 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 IEEE802.11 basic access mechanism, assuming T_{PHY} as the time duration of PHY header plus propagation delay *δ*, and T_{ACK} is the time duration used to transmit an ACK frame, Ts and Tc can be expressed as

$$\begin{cases} T_s=T_{PHY}+T_p+SIFS+T_{PHY}+T_{ACK}+DIFS \\ T_c=T_{PHY}+T_p+DIFS \end{cases} \tag{12}$$

Here the frame size is assumed to be of fixed length. Remember that equation (6) shows the value τ is only determined by W. Using the parameters listed in Table. I, the relation of throughput *(S)* and contention window *(W)* in DCF/CCW with different network scales is depicted in Fig.2.

TABLE I
DSSS SYSTEM PARAMETERS AND ADDITIONAL PARAMETERS USED TO OBTAIN NUMERICAL RESULTS

Channel Bit Rate	1 Mbps
Slot Time	20μs
SIFS	10μs
DIFS	50μs
Propagation Delay	1μs
T_{PHY}	192μs+ Propagation Delay
MAC Data Frame	1024 Bytes
MAC ACK Frame	14 Bytes

TABLE II
COMPARISON OF MAXIMUM THROUGHPUT FOR DIFFERENT NETWORK SCALES

Network Scale	Maximum Throughput	Optimal W
n=5	0.8833	133
n=10	0.8802	282
n=15	0.8792	420
n=20	0.8787	579

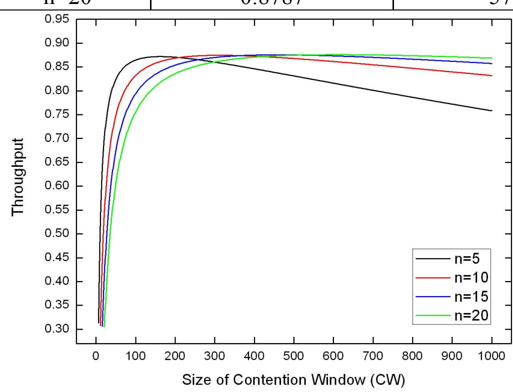

Fig.2 the Relation of S and W in DCF/CCW with Different Network Scale

From Fig.2 we can see that for a given number of n, as the value of W increases from 1 to 1000, the throughput firstly increases, then decreases. The throughput of a network with small scale decreases faster after its maximum point. While the throughput of network with large scale increases slower before its maximum point. But what attracts us is that the networks with different scale almost obtain the same maximum throughput, which is listed in Table. II. This gives us an intuition that if the *CCW* is properly selected based on the network state (e.g. the number of stations that competing the wireless channel); the maximum throughput can be obtained. This is just the key point of DCF/CCW optimization mechanism that will be introduced later.

3.3. Access Delay Analysis

Definition: The Access Delay (AD) is the total time for a station since a frame begins to contend for the channel until the contention is successful and the frame begins to be transmitted.

To calculate the value of AD, let us firstly recall the average length of a slot time d, which is ever used as the denominator of the throughput S.

$$d = P_t \cdot (T_s \cdot P_s + T_c \cdot P_c) + P_i \cdot \sigma \qquad (13)$$

A station having a frame to transmit uniformly chooses an integer in the range (0, W−1) as the backoff slot and then begins the backoff procedure. When the backoff counter decreases to zero, the frame is transmitted. If the frame is successfully transmitted during its first transmission, the average waiting time for this frame to access the channel since its contention is expressed as

$$D_1 = E[backoff\_slots] \cdot d = \frac{W-1}{2} \cdot d \qquad (14)$$

When the size of contention window is fixed; the AD of each retransmission is all the same. If a frame is transmitted for i times, then the AD of this frame is

$$D_i = i \cdot D_1 \qquad (15)$$

Considering the retry limit r, the average AD of a frame is

$$D = E[D_i] = \sum_{i=1}^{r} D_i \cdot P_c^{i-1}(1-P_c) = D_1(1-P_c)\sum_{i=1}^{r} i \cdot P_c^{i-1} \qquad (16)$$

Using the parameters listed in Table. I, the relation of average AD and contention window with different number of competing terminals is depicted in Fig.3.

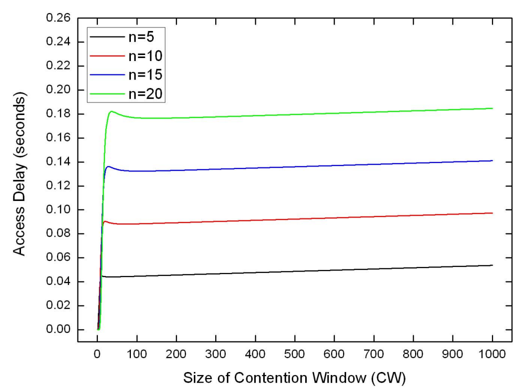

Fig.3 the Relation of D and W in DCF/CCW with different Network Scale

From Fig.3 we can get a general idea that the average AD time for different network scales is very different. But for a given network, when the size of contention window is larger than the number of competing terminals, the average AD time does not jitter much as the size of contention window increases.

4. Description of Optimal-DCF/CCW

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Recall the equation (11) and reassemble it as

$$S = \frac{T_p}{T_s - T_c + \sigma \cdot \dfrac{\dfrac{T_c}{\sigma}[1-(1-\tau)^n] + (1-\tau)^n}{n\tau(1-\tau)^{n-1}}} \tag{17}$$

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

$$\frac{n\tau(1-\tau)^{n-1}}{\dfrac{T_c}{\sigma}[1-(1-\tau)^n] + (1-\tau)^n} = \frac{n\tau(1-\tau)^{n-1}}{\dfrac{T_c}{\sigma} - (1-\tau)^n(\dfrac{T_c}{\sigma} - 1)} \tag{18}$$

Imposing the above derivative to 0 with respect to τ, we obtain, after some simplifications, the following equation:

$$\tau = \frac{\sqrt{\left[n + 2(n-1)(T_c/\sigma - 1)\right]/n} - 1}{(n-1)(T_c/\sigma - 1)} \approx \frac{1}{n} \cdot \sqrt{\frac{2\sigma}{T_c}} \tag{19}$$

This is the optimal transmission probability τ that each station should adopt in order to achieve maximum throughput performance. Considering equation (6), we obtain the optimal size of *CCW* to maximum throughput performance as

$$W_{opt} = n \cdot \sqrt{\frac{2T_c}{\sigma}} - 1 \tag{20}$$

Equation (20) tells us that if we have successfully obtained the number of competing terminals in a given network [6], it is easily to calculate the optimal *CCW* to maximize the system throughput. E.g. when using the parameters listed in Table.1, we get a general knowledge that the optimal *CCW* is always about 29 times of the number n.

Now let us give a detailed description of the optimal-DCF/CCW:

1) A station estimates the network states information, such as the number n of competing terminals.
2) Based on the above information, a station determines its W_{opt} according to equation (20). This W_{opt} can be adjusted whenever the network states are changed.
3) In DCF/CCW, there is no need of exponential backoff. When a packet arrives, the station randomly chooses an integer from a uniform distribution over the interval (0, W-1) to determine the Backoff Timer, and then begin to perform the backoff procedure.
4) The backoff procedure is the same as DCF. When the channel is idle, the backoff counter decreases by one for each time slot; but when the channel is busy, the backoff counter is frozen. The packet is transmitted whenever the Backoff Timer reaches zero.
5) If a collision happens or the ACK frame is not received properly, the station chooses another integer still from (0, W-1) as the backoff slots, and then begins to perform a new backoff procedure to retransmit the former frame.

From the above description, we can see that the most obvious difference between IEEE802.11 DCF and optimal-DCF/CCW is that the latter one can directly give the station an optimal contention window while the former one has to encounter repeated collisions before getting the proper contention window. Another difference is that in DCF, after a packet is transmitted successfully, the contention window is adjusted to the minimum contention window, which is a constant based on the PHY technique. While in optimal-DCF/CCW, the contention window is only related to the network states; whenever the network state doesn't change, the contention window is not adjusted. All these two differences are of great importance, as comparing with DCF, the optimal contention window obtained from the network state has significantly avoided many potential collisions, which is helpful to improve the performance of IEEE 802.11 WLANs

5. Simulation to Evaluate Opti-DCF/CCW

To evaluate the performance of optimal-DCF/CCW, OPNET is used to compare it with IEEE802.11 DCF. Assume a wireless Ad Hoc network covers an area of 100m×100m. At first, there are 5 competing terminals. Then the number of competing terminals increases in a step of 5 every 60 seconds until the simulation ends at 300 seconds. Neither hidden terminals nor capture exist. Each station works in saturated condition and uses the basic access mode. The other parameters used in this simulation list in Table.1. We suppose each station has successfully got the number of competing terminals (20), and they adjust their W_{opt} in optimal-DCF/CCW according to equation.

Fig.4 is the comparison of saturation throughput. The throughput of DCF decreases as the number of competing terminals increases, because the collisions increase. But in optimal-DCF/CCW, the optimal *CCW* reduces the collision probability to a much lower level. Thus the throughput of optimal-DCF/CCW does not decease even when the network scale become larger. The normalized throughput of optimal-DCF/CCW is about 0.86, which is nearly the maximum theoretical throughput in Table. II. The advantage of optimal-DCF/CCW is much more evident when the network scale is large. E.g. in the time interval of 240~300 second when there are 25 competing terminals, the optimized throughput is about 25% higher than IEEE802.11 DCF.

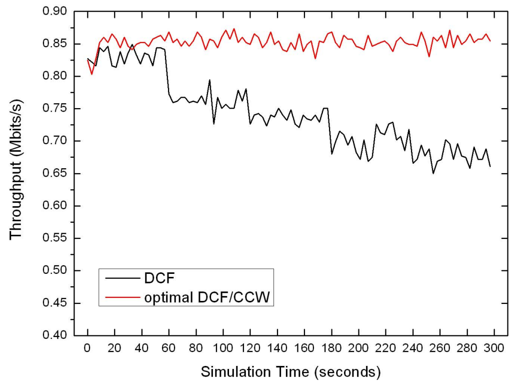

Fig.4 Comparison of Saturation Throughput

The simulation result in Fig.5 is interesting. Although the optimal *CCW* is implemented to get the maximum throughput, the access delay is also optimized. The main reason is that the optimal *CCW* has been used to avoid many potential collisions, i.e. decreasing the collision probability Pc in equation (16). A frame can be successfully transmitted with fewer collisions. Thus the access delay in optimal-DCF/CCW is much lower than IEEE802.11 DCF. From this figure we can also get a general knowledge that the optimal-DCF/CCW has a much smoother jitter, especially when network scale is larger.

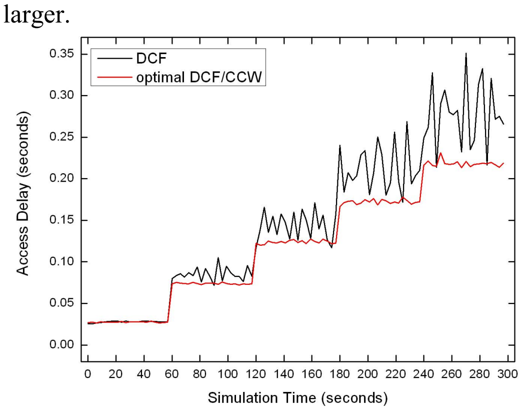

Fig.5 Comparison of Media Access Delay

6. Conclusion

In this paper, we propose the optimal-DCF/CCW for IEEE802.11 WLANs. The analysis has proved the feasibility of this idea. The theoretical maximum throughput of different network scale is nearly the same, in case a proper *CCW* is selected. But the access delay is less sensitive to the size of *CCW* for a given network scale. All this knowledge tells that an optimal *CCW* exists, and can be used to improve the performance of IEEE802.11 WLANs. The formula to calculate this optimal *CCW* shows that the value of optimal *CCW* is only related to the network states, such as the number of competing terminals. So our optimization mechanism of optimal-DCF/CCW is to directly give the station an optimal *CCW* according to the network states. This mechanism has successfully solved the problem existing in DCF that a station has to encounter several collisions until getting a proper minimum contention window. Computer simulation tells us that comparing with the standard DCF, the throughput and access delay have been improved a lot in case of optimal-DCF/CCW, since many potential collisions have been avoided due to the optimal *CCW*.

The using of optimal-DCF/CCW needs to obtain the network states information. So the further research should focuses on the developing of an efficient and accurate estimation mechanism.

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