Using a Constant Contention Window to Maximize the Throughput of IEEE 802.11 WLANs

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Abstract

An optimal constant contention window is introduced from mathematical analysis to maximize the throughput of IEEE802.11 WLANs. Simulation results show that this optimization mechanism is efficient to improve the system throughput for different network scales.

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, 3, 4, 5, 6 and 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 contention window is reduced to the PHY-based minimal contention window whenever the transmission is successful.

The introduction of DCF scheme is partially under the assumption that the station does not know any information about the network states at a given time. However, former literatures have shown that some network states information can be obtained by monitoring the channel [8, 9, 10 and 11]. And some of them have begun to use this information to optimize the performance of IEEE802.11 WLANs. [9] selected the contention window according to the number of competing terminals. [10] gave a complex adaptive mechanism to select the appropriate size of the contention window for a given congestion level. [11] provided an optimal constant-window based on the monitored optimal transmission probability.

In this paper, we propose to use a novel MAC protocol, DCF with Constant Contention Window (DCF/CCW) to maximize the system throughput of IEEE802.11 WLANs. The main idea of DCF/CCW is to directly give the competing stations a CCW for the backoff procedure. There is no concept of maximum contention window or minimum contention window in DCF/CCW. Our analysis proves that the optimal CCW to maximize the system throughput is only related to the network states such as the number of competing terminals. So based on the fact that some necessary network states information can be obtained through monitoring the channel [7, 8, 9 and 10], we propose the optimization mechanism, optimal-DCF/CCW. The optimal-DCF/CCW is implemented in two steps. Firstly, each station monitors the channel and estimates the necessary network sates information. Secondly, based on the estimated states information, every station directly selects its optimal CCW. This directly obtained optimal CCW doesn't double even in case of collisions, and whenever the network states are not changed, the value of the optima CCW is not adjusted. This is why we call it "Constant Contention Window".

The paper is organized as follows. In section 2 the throughput of DCF/CCW is analyzed under the proposed mathematical model. The detailed description of optimal-DCF/CCW in IEEE802.11 WLANs is depicted in section 3. And computer simulation to validate the performance of optimal-DCF/CCW is shown in section 4. Section 5 provides the concluding remarks

2 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 choose another backoff slots from (0, *CCW*-1) to retransmit the former packet. In this section we analyze 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

2.1 Frame Transmission Probability

Consider a fixed number of competing terminals in saturation conditions. 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

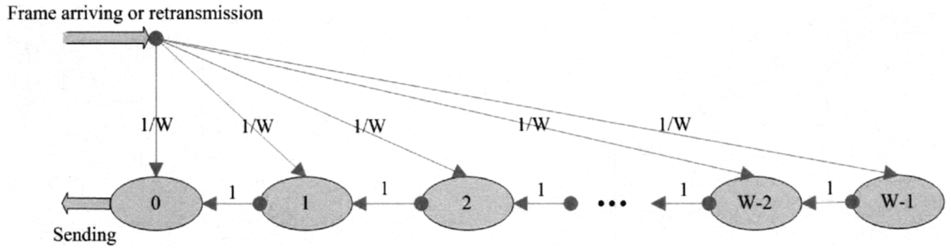

Fig.1 Markov Chain for the Backoff Window Size

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

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

The first equation in (1) 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

$$b_k = \lim_{t\to\infty} P\{b(t)=k\}, k\in(0,W-1) \quad (2)$$

be the stationary distribution of the chain. Note that

$$b_k = \frac{W-k}{W} b_0, k\in(0,W-1) \quad (3)$$

In Equation (3), all values of b_k are expressed as function of the value b_0. Thus it is not difficult to obtain

$$1=\sum_{k=0}^{W-1} b_k = \sum_{k=0}^{W-1} b_0 \cdot \frac{W-k}{W} = b_0 \sum_{k=0}^{W-1}(1-\frac{k}{W}) = b_0 \cdot \frac{W+1}{2} \quad (4)$$

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:

$$\tau = b_0 = \frac{2}{W+1} \quad (5)$$

2.2 Throughput Analysis

To analyze the performance of constant contention window in DCF, let us firstly analyze what happens in a random 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, each transmits with a probability τ, then

$$P_i = (1-\tau)^n \quad (6)$$

Let P_{tr} be the probability that there is at least one transmission in the considered slot time. Based on Equation (6), we get

$$P_{tr} = 1-(1-\tau)^n \quad (7)$$

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.

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (8)$$

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

$$P_c = 1-P_s = \frac{1-(1-\tau)^n - n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \quad (9)$$

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

$$S = \frac{T_p \cdot P_s}{T_s \cdot P_s + T_c \cdot P_c + \sigma \cdot P_i} \quad (10)$$

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, T_s and T_c can be expressed as

$$\begin{cases} T_s = T_{PHY} + T_p + SIFS + T_{PHY} + T_{ACK} + DIFS \\ T_c = T_{PHY} + T_p + DIFS \end{cases} \quad (11)$$

Here the frame size is assumed to be of fixed length. Remember that Equation (5) shows the value τ is only determined by W. When using the parameters listed in Table.1, the relation of throughput (S) and contention window (W) in DCF/CCW with different number of competing terminals is depicted in Fig.2.

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.1 DSSS System Parameters and Additional Parameters Used to Obtain Numerical Results.

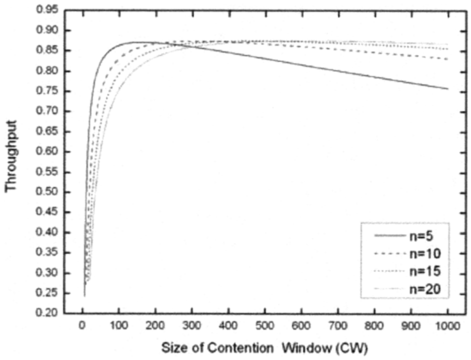

Fig.2 the Relation of *S* and *W* in DCF/CCW with Different Network Scale

Network Scale	Maximum Throughput	Optimal Contention Window
n=5	0.8719	158
n=10	0.8745	307
n=15	0.8754	460
n=20	0.8759	609

Table.2 Comparison of Maximum Throughput for 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 value is obtained. But what attracts us is that the networks with different scales almost obtain the same maximum throughput, which is listed in Table.2. 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 bellow.

3 Description of Optimal-DCF/CCW

As we have mentioned before, the maximum system throughput is almost the same for different network scales. The optimization mechanism of optimal-DCF/CCW focuses on the optimal CCW to reach the theoretical maximum throughput.

Recall the Equation (10) and reassemble it as

$$S=\frac{T_p}{T_s-T_c+\dfrac{T_c[1-(1-\tau)^n]+\sigma(1-\tau)^n}{n\tau(1-\tau)^{n-1}}} \quad (12)$$

As T_s, T_c, T_p and σ are constants in Table.1, the throughput *S* is maximized when the following quantity is maximized:

$$\frac{n\tau(1-\tau)^{n-1}}{T_c[1-(1-\tau)^n]+\sigma(1-\tau)^n}=\frac{n\tau(1-\tau)^{n-1}}{\dfrac{T_c}{\sigma}+(1-\tau)^n(\dfrac{T_c}{\sigma}-1)} \quad (13)$$

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

$$\tau=\frac{\sqrt{\left[n+2(n-1)(T_c/\sigma-1)\right]/n}-1}{(n-1)(T_c/\sigma-1)}\approx\frac{1}{n}\cdot\sqrt{\frac{2\sigma}{T_c}} \quad (14)$$

This is the optimal transmission probability τ that each station should adopt in order to achieve maximum throughput performance. Considering Equation (5), we obtain the optimal size of CCW to maximum system throughput performance as

$$W_{opt}=n\cdot\sqrt{\frac{2T_c}{\sigma}}-1 \quad (15)$$

Equation (15) 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, the general knowledge is 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 (15). This W_{opt} can be adjusted whenever the network states 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 throughput performance of IEEE 802.11 WLANs

4 Simulation to Evaluate Optimal-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 30 seconds. After 120 seconds, the number of competing terminals decreases in a step of 5 every 30 seconds until the simulation ends at 210 second. 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, and they adjust their W_{opt} in optimal-DCF/CCW according to Equation (15).

Fig.3 is the comparison of saturation throughput. The throughput of DCF decreases as the number of competing terminals increases because the collision increases. 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 large. The normalized throughput of optimal-DCF/CCW is about 0.85, which is nearly the maximum theoretical throughput in Table.2. The advantage of optimal-DCF/CCW is much more evident when the network scale is large. E.g. in the time interval of 90~120 second when there are 20 competing terminals, the optimized throughput is about 25% higher than IEEE802.11 DCF.

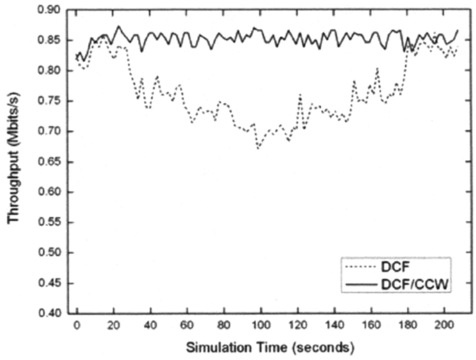

Fig.3 Comparison of Saturation Throughput

5 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. This knowledge tells that an optimal CCW exists, and can be used to improve the system throughput 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 system throughput has been improved a lot in optimal-DCF/CCW, since many potential collisions have been avoided due to the optima 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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