Delayed contention DCF MAC protocol for IEEE 802.11 wireless LANs

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Abstract—**This paper proposes a new MAC protocol called delayed contention DCF (DC-DCF) with a built-in traffic shaping feature for IEEE 802.11 wireless LANs. By suspending a number of active stations, the new protocol significantly reduces the probability of collision and provides better quality of service. The complexity of implementing such a protocol is low and the related parameter is easily determined. Simulation results show that the proposed protocol outperforms DCF in terms of throughput, the probability of collision, and average delay.**

Keywords- IEEE 802.11 MAC, backoff, traffic shaping

I. INTRODUCTION

In recent years, wireless local area networks (WLANs) have been widely used thanks to their ease of deployment and low cost. The primary medium access control (MAC) protocol of IEEE 802.11[1] is called distribution coordination function (DCF). By DCF, all stations contend for the wireless channel using the carrier sense medium access with collision avoidance (CSMA/CA) protocol that adopts a slotted binary exponential backoff (BEB) scheme to avoid collisions.

The performance of the DCF has been extensively analyzed and evaluated. Bianchi [2] developed a two dimensional Markov Chain to compute the saturation throughput of the IEEE802.11 DCF protocol. Chatzimisios et al. [3-5] extended Bianchi's work for the case with a finite retry limit and computed the average packet delay in addition to the throughput. Afterwards, a new approach for deriving the service time delay generating function is presented by [6]. However, those papers [2-7] are limited to the average delay. More recently, the authors in [8, 9] proposed analytic models to estimate the delay distribution in the MAC layer with given system parameters such as the number of stations, the minimum contention window, and the retry limit. Although previous research indicated that the performance heavily depends on the parameters, none provided a method to adjust the parameters for the best performance. With the observation that maximum throughput is achieved when the collision probability is around 0.196, Zhai et al. [10] proposed a method to maintain high throughput for large networks by controlling user traffic. However, the means to control user traffic remains an open issue. One traditional way to control user traffic is to add a traffic shaper for each station, but obviously, this would be impractical for today's low cost WLAN products.

The fundamental goal of the BEB scheme is to reduce collision rates under heavy loads, by doubling the contention window of collided stations. The design is good from the perspective of the system, but not fair among packets. The doubled contention window forces a collided packet to wait longer and suffer large delay. On the other hand, packets without collision can be transmitted quickly. As a result, the delay variation of a station is often considerable, which is harmful to real-time applications. These observations motivated us to develop a new MAC protocol to mitigate the above-mentioned issues.

Since the collision between stations is the root cause, the basic idea is to reduce the number of stations in contention by suspending some stations with backlog. A simple question arises: "which station can be postponed?" This paper proposes a simple strategy to suspend the station which just finishes a successful transmission for some slots. According to the simulation results, the proposed protocol can well control the probability of collision and provide isolation between stations. As a result, the wireless networks can provide a certain level of guarantee in packet delay. This paper is organized as follows. Section 2 presents a brief overview of the IEEE 802.11 DCF protocol and the new proposed protocol named delayed contention DCF (DC-DCF). The mathematical analysis based on the Markov chain model is shown in Section 3. Section 4 shows simulation results to demonstrate the advantages of the new protocol. Finally, Section 5 presents conclusions.

II. DELAYED CONTENTION DCF PROTOCOL

The DCF protocol is based on a standard Ethernet-like contention-based service and adopts a slotted Binary Exponential Backoff (BEB) scheme to avoid collisions. When a station has a packet to transmit, it needs to sense the wireless medium. If the medium is busy, it defers the transmission until the medium is idle. If the medium is detected to be idle for a time interval, which is a DCF Inter-Packet Space (DIFS), the source station starts a backoff operation with a randomly-selected backoff count value. The backoff counter is decreased by one after an idle slot time and is frozen when the source station detects that the medium is busy. When the backoff counter reaches zero, the source station starts transmitting its packet. If multiple stations count down to zero at the same time, they transmit simultaneously and a collision occurs. When the destined station receives this packet successfully, it transmits an immediate positive acknowledgment (ACK) packet back after a time interval, which is a Short Inter-Packet Space (SIFS). After the source station receives the ACK packet, the transmission is successfully completed. If the

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$$b_{0,0}=\frac{1}{(C+f)}, \text{ where} \tag{6}$$

$$f=\begin{cases} \dfrac{W(1-(2p)^{m+1})(1-p)+(1-2p)(1-p^{m+1})}{2(1-2p)(1-p)}, & m \le m'. \\ \dfrac{W(1-(2p)^{m'+1})(1-p)+(1-2p)(1-p^{m+1})+W2^{m'}p^{m'+1}(1-2p)(1-p^{(m-m')})}{2(1-2p)(1-p)}, & m > m'. \end{cases}$$

source station does not receive the ACK packet, it schedules a retransmission and the backoff operation restarts.

The backoff count value is chosen uniformly in [0, W_i -1] where W_i is the current contention window size at ith retry. At the first transmission attempt, W_0 is equal to the minimum contention window size denoted by W. When the station detects a fail transmission, it will double W_i until W_{max} is reached. Let m and m' be the retry limit and the maximum number that W_i can be doubled, respectively. We have

$$W_i=\begin{cases} 2^i W, & i \le m', \\ 2^{m'} W, & i > m'. \end{cases} \tag{1}$$

When the station fails to transmit at the mth retry, it drops the current packet and starts a new transmission with $W_0 = W$.

The basic idea behind the proposed MAC is to reduce the number of stations contending wireless medium during the backoff process of a tagged station. Our approach is to postpone the first transmission attempt of a new head of line packet for numerous slots. Because the contention cycles of some active stations may be delayed, our scheme is named delayed contention DCF. In this manner, collided packets, if they exist, will have a higher chance of being transmitted and their delay can be shortened. In addition, the traffic entering the network can be shaped because every packet reaching the head of line is postponed. As a result, the collision probability can be controlled and channel utilization is improved. Most important of all, this idea could be implemented very easily by modifying the calculation of the backoff counter in a station as follows.

$$\text{Backoff counter} = \begin{cases} C+\text{random}(W_o), & \text{for 1st transmission,} \\ \text{random}(W_i), & \text{for retransmission,} \end{cases} \tag{2}$$

where random(W_i) is a function that uniformly generates a random number in [0, W_i -1], and C is a constant variable denoting how many extra slots a station needs to backoff for the first transmission of a head of line packet. Other parts of the MAC operation remain the same as in the DCF protocol.

III. Mathematical Analysis

This paper adopts the Markov chain model presented in [3-5] to analyze the proposed protocol. Fig. 1 shows the model for a tagged station, where each state ($s(t)$,$b(t)$) represents its current retry stage and backoff counter. Let $b_{i,k}$ be the stationary distribution of the of the Markov chain. Assuming that each transmission attempt has the same collision probability denoted by p, we have

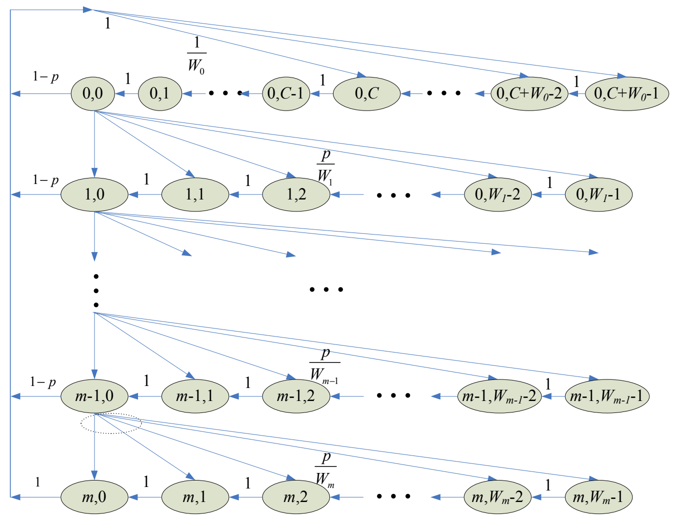

Fig. 1. The Markov chain model of the proposed system.

$$b_{i,0}=b_{i-1,0}*p \;\rightarrow\; b_{i,0}=p^i b_{0,0} \text{ for } 0<i\le m. \tag{3}$$

Since the chain is regular, we have

$$b_{i,k}=\begin{cases} \dfrac{W_0-k}{W_0}b_{i,0}, & \text{for } i>0, \\ \dfrac{W_0-k+C}{W_0}b_{0,0}, & \text{for } i=0 \text{ and } k>C, \\ b_{0,0}, & \text{for } i=0 \text{ and } k\le C \end{cases} \tag{4}$$

By using the normalization condition, we have

$$1=\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k}=\sum_{k=0}^{C+W_0-1}b_{0,k}+\sum_{i=1}^{m}\sum_{k=0}^{W_i-1}b_{i,k}$$
$$=b_{0,0}(C+\sum_{i=0}^{m}\frac{p^i(W_i-1)}{2})=b_{0,0}(C+f). \tag{5}$$

Finally, we can derive $b_{0,0}$ as shown in (6). By adding the probabilities of the states with zero backoff counter, the transmission probability in a slot, which is denoted by τ, can be calculated by:

$$\tau=\sum_{i=0}^{m}b_{i,0}=\frac{1-p^{m+1}}{1-p}b_{0,0}. \tag{7}$$

In the following, let us consider the worst case where N contending stations always have packets for transmission. The collision probability can be calculated by:

$$p = 1-(1-\tau)^{N-1}. \tag{8}$$

Equations (7) and (8) form a nonlinear system with two unknowns τ and p for a given C. The nonlinear system can be solved by numerical methods and has a unique solution. Then the average throughput and the average delay at the MAC layer can be calculated by the same formulas in [3-5].

One major difference between the proposed scheme and the standard DCF is that a new variable C is introduced. Since the collision probability decreases with an increase in C, a straightforward question is how to select a proper value for C. As mentioned previously, Zhai et al. [2] pointed out that normalized throughput arrives at the maximum value of approximately p=0.196, which inspired us to choose a proper C to meet the criterion for a given network size. By substituting p=0.196 into (6), (7), and (8), we can derive the solution to C. After rounding to the nearest integer, we get the best value denoted by C^* as shown in (9).

$$C^* = round\left(\frac{1-p^{m+1}}{(1-p)(1-\sqrt[N-1]{1-p})} - f\right). \tag{9}$$

According to the standard, the typical value of m' is 5. Since a packet is dropped when the retry limit is reached, the drop probability is

$$p_{drop} = p^{m+1}. \tag{10}$$

The collision probability for the DCF protocol increases dramatically with the network size. As the network size becomes large, the drop probability is considerable. On the other hand, the DC-DCF protocol allows us to control the collision probability and the drop probability. This paper selects m=6 and the drop probability can be kept very small. After some calculations, we list the values of C^* for different N in Table 1.

IV. Simulation Results

This section presents two experiments to demonstrate the advantages of the DC-DCF protocol. The first experiment shows the worst case performance, while the second one considers a more realistic scenario created by the NS2[11] simulator. All simulations were conducted with the RTS/CTS mechanism, and the system parameters are listed in Table 2.

A. Saturated network

The first simulation was conducted by Matlab to evaluate the performance for the saturated case. Fig. 2 shows the average throughput and the probability of collision against N. The average throughput of DCF decreased with N as expected due to high collision rates. On the contrary, DC-DCF was able to maintain a high throughput because the number of contenting stations was well-controlled. This was verified by the flat curve of collision probability for the DC-DCF protocol. The resulting collision probability is very close to 0.196, which proves the effectiveness of the model presented in the section 3. Notice that a high collision probability also implied a high drop probability, because packets with (m+1) collisions were dropped by the WLAN. Let us take N=30 for example. The drop probabilities for DCF and DC-DCF were $4.1\text{x}10^{-3}$.

Table 1. C^* for W=32, m'=5, m=6 versus the number of stations

N	10	15	20	25	30	35	40	45	50
C^*	25	54	82	111	139	168	196	225	253

Table 2. System parameters

Parameter	Value
PHY rate	54 Mbps
SIFS	16μs
DIFS	34μs
T_{RTS}	46.67μs
T_{CTS}	38.67μs
T_{ACK}	38.67μs
Slot time	9μs
Preamble+header	20μs
W	32
m'	5
m	6

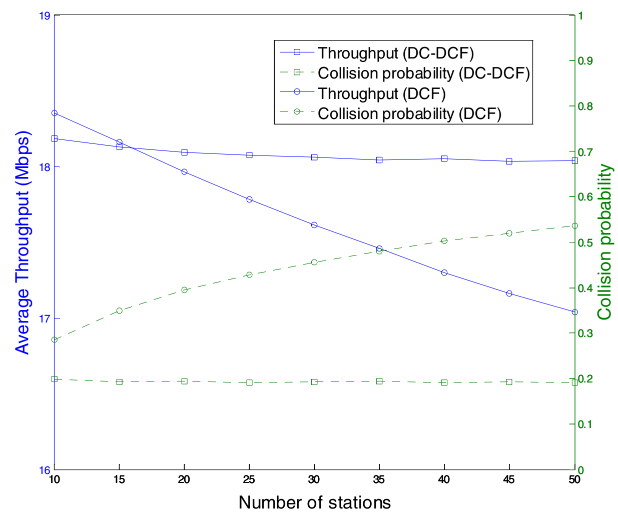

Fig. 2 Throughput and collision probability against the number of contending stations

and $1.1\text{x}10^{-5}$, respectively. It is obvious that DCF suffered from a high drop probability for large networks. Though it can be mitigated by increasing m', the delay variation is also affected too

The MAC delay is defined as the time interval from the instant that a packet reaches the head of its queue to the instant that it is successfully transmitted to the destination. Fig. 3 shows the delay distribution of successfully transmitted packets for N=30 in the MAC layer. Because the distribution of DC-DCF was more concentrated, DC-DCF possessed a great traffic shaping feature, which was well-suited to jitter-sensitive applications. Moreover, the tail distribution of DC-DCF, shown in the right part of Fig. 3, decayed more sharply.

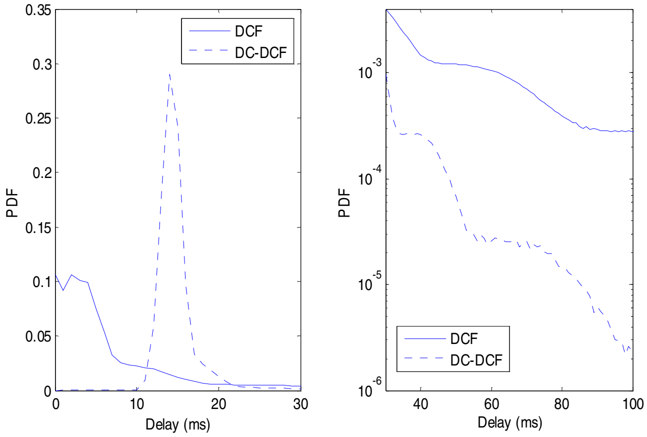

Fig. 3 The PDF of the MAC delay for N=30

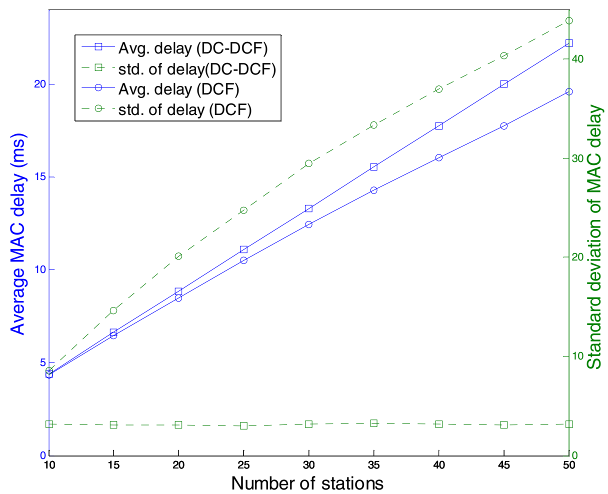

Fig. 4 The delay in the MAC layer

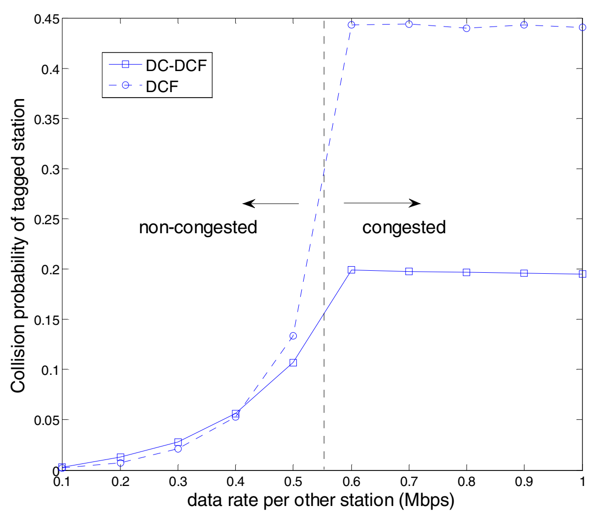

Fig. 5 The collision probability of the tagged station

This means that DC-DCF is able to provide better delay performance because the probability that the delay is over a threshold can be significantly reduced. Fig. 4 shows the average MAC delay and the standard deviation of the MAC delay. One drawback of DC-DCF is that the average MAC delay under the saturated networks is increased slightly (approximately 6.9% for the case of N=30). Nevertheless, DC-DCF had an interesting property that the standard deviation of MAC delay was almost constant, while that of DCF increased with the network size. According to the classical queueing theory, the queueing delay for an M/G/1 is

$$d_{queue} = \frac{\lambda \overline{x^2}}{2(1-\rho)}, \tag{11}$$

where λ is the packet arrival rate, x is the service time, and $\rho=\lambda*\overline{x}$. If we model a station as an M/G/1 queue, the service time in the queueing model is equal to the MAC delay. Equation (11) shows that the queueing delay is proportional to the second moment of the MAC delay. Because the second moment is equal to the variance of x plus the square of $\overline{x}$, the queueing delay of DC-DCF should be much smaller than that of DCF for large networks. Next, we evaluate the proposed protocol by NS2 to verify the performance for a more realistic scenario.

B. End-to-end delay in a real network

To investigate the performance of DC-DCF under a real network, we also ran simulations by NS2 for N=30. The implementation was very easy by slightly modifying the backoff timer which is used to control the instant of transmission. When the current contention window is equal to W, extra C^* slots are added to the backoff counter of the packet in the MAC layer because it is at its first transmission attempt. We tagged the first station to see its performance under different loadings. Each station had one UDP flow which was generated according to the Poisson process with the fixed packet size equal to 1000 bytes. The data rate for the tagged station was fixed at 0.5Mbps, while the data rates for others were adjusted from 0.1Mbps to 1.0 Mbps to simulate dynamic network loading. The simulation time is 1000s. Fig. 5 shows the collision probability of the tagged station. The collision probability for DCF increased dramatically with the traffic loading as expected. On the other hand, the capability of DC-DCF to delay the contention of the first transmission effectively reduced the collision probability under heavy loads. As the data rates of other stations increased, the network became congested and similar to the saturated case. We can divide the simulations into two parts: the congested region and the non-congested region. The collision probability stayed around 0.196 at the congested region, which also validated the Markov chain model presented in Section 3.

Fig. 6 shows the end-to-end delay of the tagged station, which includes the MAC delay and the queueing delay. At the non-congested region, most packets can be sent quickly because the overall traffic in the network is light. In this case, the MAC delay dominated the end-to-end delay. Adding extra C^* slots for the first transmission attempt in DC-DCF forced the packets to wait longer such that the MAC delay is larger.

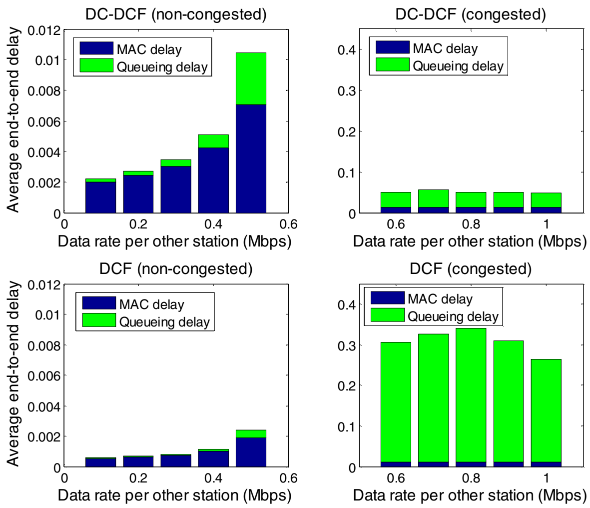

Fig. 6 The average end-to-end delay of the tagged station

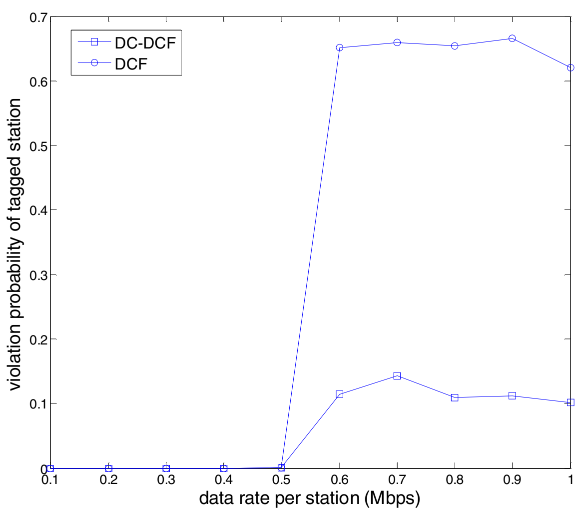

Fig. 7 The violation probability of the tagged station

Though the end-to-end delay of DC-DCF was about 5 times larger than that of DCF at the loading with 0.5 Mbps per other station, the delay caused by DC-DCF is not a problem at all for most applications. On the contrary, at the congested region, the end-to-end delay of DCF increased dramatically. Though the MAC delay of DCF was still very small, the queueing delay was extremely large due to the high collision probability. For example, about 10% of packets were transmitted successfully at the 5th transmission with the average number of total backoff slots equal to 496. If all stations were greedy, the wireless channel was often occupied by other stations during the backoff process of the tagged station. By DC-DCF, because the collision probability was well-controlled by suspending some active stations, the average end-to-end delay was about 50ms which is acceptable for real applications. Let us recall the average saturated throughput in Fig. 2 for DCF is over 17.5Mbps, which means that each station can share over 0.58Mbps. In our simulations, the data rate of the tagged stations was only 0.5Mbps, but the extremely large delay (about 300ms) cannot meet the requirement of typical applications.

Assume that there is an application with the delay bound of 100ms. We say that a packet violates the delay bound if it is lost or its end-to-end delay is larger than the bound. Fig. 7 shows the violation probability for the tagged station. By DC-DCF, about 90% of packets can meet the requirement even at the congested region. In summary, this experiment shows the power of traffic shaping which provides isolations between stations when the network is congested. Though the delay is larger than that of DCF in light loadings, it still very small and far below the requirement of most applications.

V. CONCLUSIONS

Traffic shaping is indispensible to control the traffic loading and guarantee QoS. This paper provides a simple and effective scheme, with which WLANs are capable of the shaping feature. Simulation results have shown that DC-DCF maintains high throughputs and significantly reduces the queueing delay. In addition, with new MAC features such as packet aggregation or burst transmission, we believe that DC-DCF could generate additional benefit, because stations would be able to collect more packets to form an aggregated packet or a burst due to delayed contention.

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