Abstract—In IEEE 802.11[1] wireless LANs based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), parameters such as contention window (CW) significantly affects its throughput performance. In this paper, we propose a novel CW control scheme in order to achieve the high throughput performance in dense user environments. While the standard CSMA/CA mechanism employs an adaptive CW control according to the number of packet retransmissions, the proposed scheme uses the optimum CW size, which is a function of the number of terminal stations (STAs). In the proposed scheme, an access points (AP) estimates the number of STAs from the measured packet collision probability, and derives the optimum CW size based on a theoretical analysis using a Markov chain model. With simulation experiments in a dense environment, we evaluate the performance of the proposed scheme and show that it significantly improves the throughput performance.

Keywords—IEEE802.11 MAC; contention window; transmission efficiency;

I. INTRODUCTION

The number of wireless devices with the IEEE 802.11 standard[1] such as laptop PCs, smart phones is drastically increased in recent years. In a dense user environment, we need to reconsider the network design problem of wireless LANs, because the traditional IEEE 802.11 MAC protocol is not designed in such an environment. Actually, in the IEEE 802.11 standard, a new IEEE 802.11 standard, packet transmission techniques in the dense environment is being discussed.

In this paper, instead of proposing a new IEEE 802.11 MAC protocol, we investigate how the existing MAC protocol should be designed in the dense environment. In particular, we focus on the backoff algorithm, which is one of the most important components of the MAC protocol to achieve higher throughput performance. In the IEEE 802.11 MAC, each terminal station transmits a packet by randomly choosing a time slot within the contention window. The contention window size increases with the number of packet retransmissions in order to reduce packet collisions.

We consider that in dense environments, there are two critical problems of the traditional backoff algorithm. One is that the minimum contention window, which is the initial contention window size, is assigned a small value. This mean that the contention window size is not optimized for the dense environment. The other is that several retransmission trials are required until the contention window size reaches an adequate value. In order to solve these problems, we propose a novel contention window control scheme in dense environments. In the proposed scheme, an access point (AP) estimates the number of terminal stations (STAs) connecting to the AP and calculates the optimum contention window size from the estimated number of STAs. When a STA tries to transmit a packet, it uses the optimum contention window size notified from the AP.

The proposed scheme has two advantages. One is that the optimum contention window size is calculated from a simple closed formula, which is obtained by a theoretical throughput analysis based on a Markov chain model[3]. The other is that no modifications are required in the transmission procedure of STAs. Therefore, the proposed scheme can be implemented only by modifying the AP.

The remainder of this paper is organized as follows. Section 2 discusses the conventional binary backoff algorithm and explain the basic idea of the proposed scheme. Section 3 describe the proposed scheme in detail. Section 4 evaluates the performance of the proposed scheme with simulation experiments and the theoretical analysis. Finally, Section 5 concludes this paper.

II. THE BINARY EXPONENTIAL BACKOFF ALGORITHM AND THE ISSUE OF CONVENTIONAL SCHEME

Figure 1 shows an example of packet transmissions with CSMA/CA in the IEEE 802.11 MAC. Interested readers may refer to the IEEE 802.11 standard for detailed descriptions of the packet transmission procedure. In the MAC protocol, a binary exponential backoff algorithm is used to implement the collision avoidance function. In this paper, we focus on the contention window (CW) size W, which affects the performance of the backoff algorithm. In the IEEE 802.11
MAC, parameters such as the minimum CW size $CW_{\text{min}}$ are assigned different values depending on the physical layer specification. We use the parameter set in the IEEE 802.11a standard, where $CW_{\text{min}}$ is set to $CW_{\text{min}} = 15$.

In the first trial of a packet transmission, the backoff algorithm set $W$ to $W = CW_{\text{min}}$. Each STA chooses a time slot randomly from $[0, CW_{\text{min}}]$, and transmit the packet on the slot. When a packet collision occurs, in order to reduce the collision probability, $W$ is doubled before retransmitting the packet. In the backoff algorithm, the CW size causes the tradeoff relationship between the collision probability and the transmission efficiency. Namely, while a small CW size may cause a larger collision probability, an excessively larger CW size may cause a significantly delayed transmission timing. Therefore, there is the optimum CW size to maximize the throughput performance.

Unfortunately, the backoff algorithm in the IEEE 802.11 standard does not optimize the CW size because STAs and the AP cannot utilize the number of STAs connecting to the AP. This approach, however, is not appropriate to achieve higher throughput performance especially in a dense network environment because $CW_{\text{min}} = 15$ is adequate for the smaller number of STAs. On the other hand, our proposed scheme aims at achieving higher throughput performance by optimizing the CW size. In our proposed scheme, we utilize the fact that the collision probability is a function of the number of STAs connecting to the AP. The number of STAs is estimated from the collision probability measured at the AP and the CW size is fixed to the optimum size, computed from the estimated number of STAs. As related work, the scheme which the number of contention STAs is estimated from idle term in the channel is proposed in [4] – [6]. Therefor, the estimation of the number of STAs from a measured collision probability.

### A. Optimal Contention Window Size using Markov Chain Model

Suppose that an STA tries to transmit a packet to the AP. Let $T$ denote the event that the STA transmit a packet into a time slot. We define state $s \in \{0, 1, \ldots, R\}$ of the STA as the number of retransmission counts, where $s = 0$ corresponds to the first transmission trial of the packet. Let $\tau$ denote the collision probability, respectively. Let $Pr(s = i \mid T)$ and $Pr(T \mid s = i)$ be the probability that the STA transmits a packet into a time slot and the probability of transmitting the packet into a time slot, respectively. The probability that the STA transmits a packet into a time slot is given by

$$Pr(T \mid s = i) = \frac{1}{1 + 2^s(CW_{\text{min}}+1)-2},$$

$$Pr(s = i \mid T) = \frac{(1 - p)^i}{1 - p^{R+1}},$$

where $p$ denotes the collision probability, respectively. Let $\tau = Pr(T)$ denote the probability that the STA transmits a packet into a time slot.
the packet at the given time slot, and \( \tau \) is obtained by

\[
\tau = \frac{1}{\sum_{i=0}^{R} \Pr(s = i) \Pr(T | s = i)}
\]

\[
= \frac{1}{\sum_{i=0}^{R} \frac{(1-p)p^i}{(1-p)^{R+1}} (1 + \frac{2^i(CW_{\text{min}} + 1) - 2}{2})}
\]

(1)

On the other hand, in the proposed scheme, the CW size is fixed to \( W \). Probability \( \tau^{(\text{prop})} \) that the STA transmits the packet is obtained by

\[
\tau^{(\text{prop})} = \frac{2}{1+W}.
\]

(2)

Let \( n (n > 0) \) denote the number of STAs. We define \( P_{\text{tx}} \) as the probability that at least one STA transmits a packet to the AP. \( P_{\text{tx}} \) is given by

\[
P_{\text{tx}} = 1 - \left(1 - \tau^{(\text{prop})}\right)^n.
\]

We also define \( P_{\text{suc}} \) as the probability that a transmitted packet is successfully received at the AP. \( P_{\text{suc}} \) is given by

\[
P_{\text{suc}} = \frac{n\tau^{(\text{prop})}(1 - \tau^{(\text{prop})})^{n-1}}{P_{\text{tx}}}.
\]

(3)

From these probabilities, the throughput \( S \) is obtained by

\[
S = \frac{P_{\text{suc}}P_{\text{tx}}L_{\text{pkt}}}{(1 - P_{\text{tx}})\sigma + P_{\text{suc}}P_{\text{tx}}T_{\text{suc}} + P_{\text{tx}}(1 - P_{\text{suc}})T_{\text{fail}}},
\]

(4)

where \( L_{\text{pkt}} \) denotes the payload size of packets, \( T_{\text{suc}} \) denotes the transmission time when a packet is successfully received at the AP, and \( T_{\text{fail}} \) denotes the transmission time when a packet is not received at the AP.

From Eq.(4), we obtain

\[
S = \frac{L_{\text{pkt}}}{T_{\text{suc}} - T_{\text{fail}} + \frac{(1 - P_{\text{tx}})\sigma/P_{\text{tx}} + T_{\text{fail}}}{P_{\text{suc}}}},
\]

\[ S \text{ is maximized when the denominator is minimized. From } \]

\[ \frac{dS}{dW} = \frac{dS}{d\tau} \frac{d\tau}{dW} = 0, \]

we obtain

\[
(1 - \tau^{(\text{prop})})^n - \frac{T_{\text{fail}}}{\sigma(n\tau^{(\text{prop})} - (1 - (1 - \tau^{(\text{prop})})^n))} = 0.
\]

We assume that \( \tau \ll 1 \). We then obtain

\[
\tau^{(\text{prop})} = \frac{\sqrt{n(n + 2(n - 1)(T_{\text{fail}}/\sigma - 1)) - n}}{n(n - 1)(T_{\text{fail}}/\sigma - 1)}
\]

\[
\approx \frac{\sqrt{2}}{n\sqrt{T_{\text{fail}}}/\sigma}.
\]

(5)

From Eq.(2), we obtain

\[
W \approx n\sqrt{\frac{2T_{\text{fail}}}{\sigma}}.
\]

(5)

Eq.(5) gives the optimal CW size to achieve the maximum throughput.

\[ \]

B. Estimation of the Number of STAs

In this subsection, the deriving scheme is illustrated in order to estimate the number of contention STAs. At first, we define collision probability \( P_{\text{col}} \) as the probability that a transmitted packet is not received at the AP.

\[
P_{\text{col}} = 1 - P_{\text{suc}} = 1 - \frac{2^n(W - 1)^{n-1}}{(1 + W)^n - (W - 1)^n}.
\]

(6)

The number \( n \) of contention STAs are derived from Eq.(6). Eq.(6) is deformed as follows,

\[
P_{\text{col}} = 1 - \frac{2^n}{(W - 1)^n - 1},
\]

\[
\approx 1 - \frac{2^n}{(1 + \frac{2}{W - 1})^n - 1}.
\]

(7)

Under the assumption that “\( W - 1 \)” is greatest, the following approximate Eq.(8) of \( P_{\text{col}} \) is obtained by the binomial theorem from Eq.(7),

\[
P_{\text{col}} \approx 1 - \frac{2^n}{W - 1 + n\frac{W - 1}{W - 1}} + \frac{n(n - 1)(\frac{W - 1}{2})^2}{2} - 1.
\]

\[
\approx 1 - \frac{W - 1}{W + n}.
\]

(8)

Therefore, we are able to obtain the estimated number \( \hat{n} \) of STAs:

\[
\hat{n} \approx \frac{P_{\text{col}}(W - 1)}{1 - P_{\text{col}}} + 1.
\]

(9)

IV. PERFORMANCE EVALUATION

We evaluate the performance of the proposed scheme with simulation experiments (Rivewater Modeler ver. 17.5 [8]) and the numerical results obtained from the theoretical analysis. The performance evaluation parameters shown Table 1. In this section, we consider a saturated environment, where each STA always has packets to be transmitted.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>PERFORMANCE EVALUATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base system</td>
<td>IEEE802.11a standard</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.2 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>PHY datarate</td>
<td>24 Mbit/s</td>
</tr>
<tr>
<td>Number of APs</td>
<td>1</td>
</tr>
<tr>
<td>Number of STAs</td>
<td>1 to 80</td>
</tr>
<tr>
<td>Packet size</td>
<td>1500 bytes</td>
</tr>
<tr>
<td>Slot time</td>
<td>9 ( \mu )s</td>
</tr>
<tr>
<td>DIFS</td>
<td>34( \mu )s</td>
</tr>
<tr>
<td>SIFS</td>
<td>16( \mu )s</td>
</tr>
<tr>
<td>ACK</td>
<td>28( \mu )s</td>
</tr>
<tr>
<td>Traffic</td>
<td>Saturated and uplink</td>
</tr>
<tr>
<td>CW size</td>
<td>Binary and optimal</td>
</tr>
</tbody>
</table>
of STAs is perfectly estimated by the AP. Figure 2 (a) shows the total throughput vs. the number of STAs. In the figure, lines and plots correspond to numerical results and simulation results. The dashed line represents the performance of CSMA/CA in the IEEE 802.11 MAC, which is referred to as “CSMA/CA” hereafter. The solid line represents the performance of the proposed scheme. We observe that the proposed scheme shows higher throughput performance than CSMA/CA. The throughput performance of CSMA decreases with the number of STAs increases. We also observe that the theoretical analysis agrees well with the simulation results, which validates our approach based on the Markov chain model-based throughput analysis. The effectiveness of the proposed scheme can be confirmed with Fig. 2(b), collision probability vs. the number of STAs. While the collision probability increases with the number of STAs in CSMA/CA, lower collision probability is kept in the proposed scheme.

Figure 3 shows the throughput performance vs. the number of STAs. While the solid line represents the throughput performance when the number of STAs is perfectly estimated. On the other hand, the plots represents the throughput performance when the number of STAs is estimated from measure collision probability. We observe that both results agree well with each other.

V. CONCLUSION

In this paper, we have proposed a novel contention window control scheme in the IEEE 802.11 wireless LAN. The proposed scheme estimate the number of STAs from measured collision probability, and calculates the optimum contention window size from the estimated number of STAs. Simulation experiments and numerical results obtained from the theoretical analysis show that the proposed scheme significantly improves the throughput performance in saturated environment.

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REFERENCES

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