PAPER

Analysis of an Adaptive *P*-Persistent MAC Scheme for WLAN Providing Delay Fairness*

Chih-Ming YEN[†a)], ***Student Member***, **Chung-Ju CHANG**[†], **Yih-Shen CHEN**[†], ***and*** **Ching Yao HUANG**[††], ***Nonmembers***

SUMMARY The paper proposes and analyzes an *adaptive p-persistent-based* (APP) medium access control (MAC) scheme for IEEE 802.11 WLAN. The APP MAC scheme intends to support delay fairness for every station in each access, denoting small delay variance. It differentiates permission probabilities of transmission for stations which are incurred with various packet delays. This permission probability is designed as a function of the numbers of retransmissions and re-backoffs so that stations with larger packet delay are endowed with higher permission probability. Also, the scheme is analyzed by a Markov-chain analysis, where the collision probability, the system throughput, and the average delay are successfully obtained. Numerical results show that the proposed APP MAC scheme can attain lower mean delay and higher mean throughput. In the mean time, simulation results are given to justify the validity of the analysis, and also show that the APP MAC scheme can achieve more delay fairness than conventional algorithms.

key words: *backoff, MAC, WLAN, delay variance, Markov-chain*

1. Introduction

Wireless local area networks (WLAN) have advantages, such as high transmission rate and low design complexity in medium access control (MAC) protocol. It is widely applied in hot spot cells and indoor environments for diverse applications. The MAC in IEEE 802.11 WLAN [1] is based on a carrier sense multiple access with collision avoidance (CSMA/CA) protocol, in which retransmissions of collided packets are managed by a *binary exponential backoff* (BEB) algorithm. This conventional MAC scheme, the CSMA/CA protocol with the BEB algorithm, is the most widely used scheme for data transmission because of its simplicity. However, a more collided station would have a smaller probability to access the medium. Thus a larger delay variance among stations would be incurred and this creates delay unfairness for each access of station. Therefore, an effective MAC protocol is necessary so as to reduce the delay variance of every station in each access, or say, support delay fairness in this paper.

Some algorithms to solve the fairness problem of MAC in WLAN were proposed [2], [3]. A multiplicative increase linear decrease (MILD) scheme was proposed in MACAW protocol for WLAN [2]. In the MACAW protocol, the current contention window information was included in each transmitted packet, and also a *backoff interval copy mechanism* implemented in each station copied the contention windows of the overheard successful transmitters. With the copy mechanism, the fairness performance of the MILD scheme is improved, but it also incurs a new problem. Each packet including the backoff interval information increases the overhead and decreases the channel throughput. Yamada, Morikawa, and Aoyama proposed a decentralized delay fluctuation control (DDFC) MAC mechanism [3], where the contention window is changed according the packet waiting time. The larger the packet waiting time is, the smaller the contention window will be. The DDFC in nature lessens variance of waiting time from enqueueing to successful transmission. Unfortunately, the channel utilization in DDFC is still low due to the small contention windows and high collision probabilities.

This paper proposes and analyzes an *adaptive p-persistent-based* (APP) MAC scheme for the IEEE 802.11 WLAN proposed in [4], [5]. The APP MAC scheme, installed in a station, dynamically adjusts the permission probability of transmission for the station itself, and sets the permission probability as a function of the numbers of retransmissions and re-backoffs. The station with longer packet delay, implying larger numbers of retransmissions and re-backoffs, is given higher permission probability. Therefore, the packet delay variance of station for each access can be decreased and the WLAN can provide good delay fairness for stations in each access. The Markov-chain model [6]–[9] is adopted to analyze the proposed APP MAC scheme. The performance measures such as collision probability, system throughput, and mean delay are successfully obtained. Numerical and simulation results show that the APP MAC scheme can effectively reduce the delay variance and thus achieve the delay fairness. The collision probability is decreased and the system throughput is enhanced, compared to conventional schemes. Moreover, discrepancy between numerical and simulation results is provided to corroborate the analyses. These results reveal that the analyses are quite accurate.

The rest of the paper is organized as follows. Section 2 describes the system model, and Sect. 3 introduces the APP MAC scheme. The mathematical analysis of the APP MAC

Manuscript received February 26, 2009.
Manuscript revised October 5, 2009.
[†]The authors are with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 300, Taiwan.
[††]The author is with the Department of Electronic Engineering, National Chiao Tung University, Hsinchu 300, Taiwan.
*This work was supported by National Science Council, Taiwan, under contract number NSC 93-2219-E-009-011 and Ministry of Education of Taiwan under Grants 91-E-FA06-4-4.
a) E-mail: cjchang@mail.nctu.edu.tw
DOI: 10.1587/transcom.E93.B.369

scheme is given in Sect. 4. Section 5 illustrates the performance comparisons of the APP MAC scheme and other conventional methods, such as BEB MAC and DDFC MAC, by numerical and simulation results. Finally, concluding remarks are given in Sect. 6.

2. System Model

The IEEE 802.11 distributed coordination function (DCF) adopts the CSMA/CA protocol to support asynchronous data transfer. The station can start to transmit only if the medium is sensed idle for a time interval equal to DCF interframe space (DIFS). Otherwise, the transmission is deferred and the BEB algorithm is invoked. In the BEB algorithm, the station chooses a backoff counter from contention window (W), before transmitting. At the first transmission attempt, W is set to the initial contention window, W_0; otherwise, W depends on the number of transmissions failed for the packet. The backoff counter is decremented by one at the end of each slot time, σ, as long as the medium is sensed idle, and suspended otherwise. It will be reactivated when the medium is again sensed idle for a period longer than DIFS. When the backoff counter reaches to zero, the station transmits immediately. A collision will occur when two or more stations transmit simultaneously. This kind of scheme is called *1-persistent*.

An acknowledgement packet sending from the destination station is used to response to its origination station to denote that the transmitted packet has been successfully received. If the acknowledge packet is not received, it assumes that the transmission has been corrupted. For an unsuccessful transmission, W is doubled until it reaches to the maximum value of the contention window, $W_{\max}$. For a successful transmission, if the station still has packets queued for transmission, it enters a new backoff procedure.

In the APP MAC scheme, it's backoff procedure is similar to that of the traditional CSMA/CA MAC scheme with BEB backoff algorithm, except when the backoff counter of a station in a backoff stage decreases to zero. At this instant, the station with the APP MAC scheme may transmit packet with a permission probability $\boldsymbol{P}$ or enter into a re-backoff procedure with a probability ($1-\boldsymbol{P}$). Here, the re-backoff procedure is defined as the process of that the station will remain at the same backoff stage with the same contention window. Noticeably, if $\boldsymbol{P}$ is equal to one, the APP MAC scheme turns to the CSMA/CA MAC scheme with BEB algorithm.

3. The Adaptive P-Persistent Mac Scheme

The adaptive p-persistent (APP) MAC scheme [4], [5] is based on the CSMA/CA protocol with a novel APP transmission algorithm. In which, the value of the permission probability $\boldsymbol{P}$ is adaptively adjusted, according to the state of its packet transmission, which is a function of the number of retransmissions (backoff stages), denoted by $\boldsymbol{RT}$, and the number of re-backoffs, denoted by $\boldsymbol{RB}$. It is because $\boldsymbol{RT}$ and $\boldsymbol{RB}$ can be regarded as measures of delay time of packet transmission. If a station enters into the re-backoff procedure one time, the value of $\boldsymbol{RB}$ will be added one until up to $RB_{\max}$, where $RB_{\max}$ is the maximum number of re-backoff times. When the value of $\boldsymbol{RB}$ is equal to $RB_{\max}$ and the station enters into the re-backoff procedure again, the value of $\boldsymbol{RB}$ will not be increased anymore. If a station suffers a collision, the value of $\boldsymbol{RT}$ will be added one until up to $BS_{\max}$ and the value of $\boldsymbol{RB}$ will be set to zero, where $BS_{\max}$ is the maximum number of backoff stage. When the value of $\boldsymbol{RT}$ is equal to $BS_{\max}$ and the station collides again, the station will remain with the value of $\boldsymbol{RT}$ equal to $BS_{\max}$. If a station achieves a successful transmission, values of both $\boldsymbol{RT}$ and $\boldsymbol{RB}$ will be set to zero. Consequently, the APP MAC scheme can make a station obtain a higher permission probability $\boldsymbol{P}$ at the same backoff stage if the station has a larger $\boldsymbol{RB}$; it will make a station obtain a lower permission probability $\boldsymbol{P}$ if the station is in the state with a smaller $\boldsymbol{RT}$.

More in details, for a station with the APP algorithm, $\boldsymbol{RT}$ and $\boldsymbol{RB}$ are initially zero, and $\boldsymbol{P}$ is assigned to be P_0 which is the initial permission probability chosen for the first transmission of a ready packet. Afterwards, $\boldsymbol{P}$ will be adaptively adjusted according to the function designed by

$$\boldsymbol{P} = P_0 + \frac{1-P_0}{BS_{\max}} * \left[\boldsymbol{RT} + \frac{\boldsymbol{RB}}{1+RB_{\max}}\right], \quad 0 \le \boldsymbol{RT} \le BS_{\max},\ 0 \le \boldsymbol{RB} \le RB_{\max}. \tag{1}$$

The philosophy behind Eq. (1) is that a station having larger $\boldsymbol{RT}$ and $\boldsymbol{RB}$ should be promoted to have a larger permission probability $\boldsymbol{P}$. Also, it is expected that the average waiting time spent at any $\boldsymbol{RB}$ for a given $\boldsymbol{RT}$ would be less than that spent at ($\boldsymbol{RT}$+1) and $\boldsymbol{RB} = 0$. Therefore, it is reasonable that $\boldsymbol{P}$ is increased by $(1 - P_0)/BS_{\max}$ if one more retransmission and $(1 - P_0)/[BS_{\max}*(1+RB_{\max})]$ if one more re-backoff procedure.

4. Analysis

For any station with the APP MAC scheme, define $s(m)$, $r(m)$, and $b(m)$ to be random processes of the backoff stage, the number of re-backoff, and the value of backoff counter, at time m, respectively, where $0 \leqq s(m) \leqq BS_{\max}$, $0 \leqq r(m) \leqq RB_{\max}$, and $0 \leqq b(m) \leqq W_i - 1$, $W_i = 2^i W_0$, W_i is the contention window W of the ith backoff stage. Also, define $(s(m), r(m), b(m))$ as the state of system. Assume that there are n contending stations in the system, and each station is operated in a saturation condition, denoting it always has a ready packet to transmit. The discrete-time observation points are embedded at the end of each slot time, which follows the medium if sensed idle longer than DIFS interval. The three-dimensional random process $\{(s(m), r(m), b(m))\}$ is a discrete-time Markov chain under the assumptions that both the collision probability and the packet transmission probability of a station are indifferent to its backoff procedure [6]. The collision probability of a station, denoted by p_c, is the probability of that a station transmits and at least

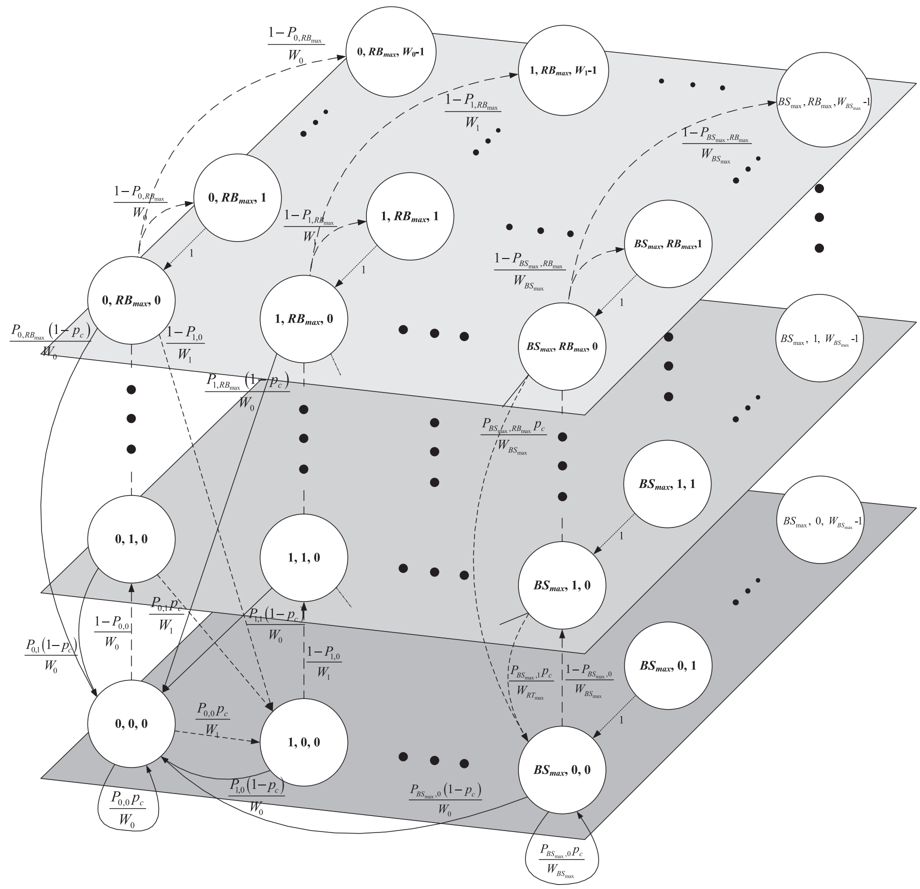

Fig. 1 State transition diagram for the APP MAC scheme.

one of the other $n-1$ stations transmits; the transmission probability of a station, denoted by p_τ, is the probability of that a station transmits at a randomly selected time slot. It is intuitive that this assumption would be more accurate as long as W_0 and n get larger. Under this assumption, p_c is supposed to be a constant value. We can obtain the state transition diagram for a station shown in Fig. 1 and state transition probabilities given by

$$P\{(i,j,k)|(i,j,k+1)\} = 1,$$
$$0 \le i \le BS_{\max},\ 0 \le j \le RB_{\max},\ 0 \le k \le W_i - 2, \quad (2)$$
$$P\{(i,j,k)|(i,j-1,0)\} = (1 - P_{i,j-1})\frac{1}{W_i},$$
$$0 \le i \le BS_{\max},\ 1 \le j \le RB_{\max},\ 0 \le k \le W_i - 1, \quad (3)$$
$$P\{(i,0,k)|(i-1,j,0)\} = P_{i-1,j}\,p_c\frac{1}{W_i},$$
$$1 \le i \le BS_{\max},\ 0 \le j \le RB_{\max},\ 0 \le k \le W_i - 1, \quad (4)$$
$$P\{(0,0,k)|(i,j,0)\} = P_{i,j}(1 - p_c)\frac{1}{W_0},$$
$$0 \le i \le BS_{\max},\ 0 \le j \le RB_{\max},\ 0 \le k \le W_i - 1, \quad (5)$$
$$P\{(BS_{\max},0,k)|(BS_{\max},0,0)\} = P_{BS_{\max},0}\,p_c\frac{1}{W_{BS_{\max}}},$$
$$0 \le k \le W_{BS_{\max}} - 1, \quad (6)$$

where $P\{(i,j,k)|(i',j',k')\} = Prob\{(s(m) = i,\ r(m) = j,\ b(m) = k)|(s(m-1) = i',\ r(m-1) = j',\ b(m-1) = k')\}$, and $P_{i,j}$ is the permission probability $\boldsymbol{P}$ at state $(i, j, 0)$. Equation (2) describes the fact that the backoff counter is decremented by 1 at the beginning of each slot time. Equation (3) accounts for the situation that the station re-backoffs again. Equation (4) indicates the case that an unsuccessful retransmission occurs at backoff stage $i-1$ thus the backoff stage is increased and the new backoff counter is uniformly chosen in the range $(0, W_i - 1)$. Equation (5) denotes what a successful packet transmission happens, thus a new packet starts with backoff stage 0 and the initial backoff counter is randomly chosen in the range $(0, W_0 - 1)$. Finally, Eq. (6) stands for that $\boldsymbol{RT}$ is not increased in subsequent packet transmissions, when the backoff stage reaches the value $BS_{\max}$.

Define $\lim_{m\to\infty}(s(m), r(m), b(m))$ as the system state at steady state. Let $b_{i,j,k} = \lim_{m\to\infty} Prob\{(s(m), r(m), b(m)) = (i,j,k)\}$ be the steady-state probability of the state $(s(m), r(m), b(m)) = (i, j, k)$. The state transition equations for $b_{i,j,k}$ can be obtained by

$$
\begin{cases}
b_{0,0,k} = \dfrac{1-p_c}{W_0}\displaystyle\sum_{i=0}^{BS_{\max}}\sum_{j=0}^{RB_{\max}} P_{i,j}b_{i,j,0} + b_{0,0,k+1}, \\
\quad 0 \le k \le W_0 - 2, \\
b_{0,0,W_0-1} = \dfrac{1-p_c}{W_0}\displaystyle\sum_{i=0}^{BS_{\max}}\sum_{j=0}^{RB_{\max}} P_{i,j}b_{i,j,0}, \\
b_{i,j,k} = b_{i,j,k+1} + \dfrac{1-P_{i,j-1}}{W_i}b_{i,j-1,0}, \\
\quad 0 \le i \le BS_{\max}-1,\ 1 \le j \le RB_{\max},\ 0 \le k \le W_i - 2, \\
b_{i,j,W_i-1} = \dfrac{1-P_{i,j-1}}{W_i}b_{i,j-1,0}, \\
\quad 0 \le i \le BS_{\max}-1,\ 1 \le j \le RB_{\max}-1, \\
b_{i,RB_{\max},k} = \dfrac{1}{W_i}[(1-P_{i,RB_{\max}})b_{i,RB_{\max},0} \\
\quad +(1-P_{i,RB_{\max}-1})b_{i,RB_{\max}-1,0}] + b_{i,RB_{\max},k+1}, \\
\quad 0 \le i \le BS_{\max}-1,\ 0 \le k \le W_{BS_{\max}} - 2, \\
b_{i,RB_{\max},W_i-1} = \dfrac{1}{W_i}[(1-P_{i,RB_{\max}})b_{i,RB_{\max},0} \\
\quad +(1-P_{i,RB_{\max}-1})b_{i,RB_{\max}-1,0}], \quad 0 \le i \le BS_{\max}-1, \\
b_{i,0,k} = \dfrac{p_c}{W_i}\displaystyle\sum_{j=0}^{RB_{\max}} P_{i-1,j}b_{i-1,j,0} + b_{i,0,k+1}, \\
\quad 1 \le i \le BS_{\max}-1,\ 0 \le k \le W_i - 2, \\
b_{i,0,W_i-1} = \dfrac{p_c}{W_i}\displaystyle\sum_{j=0}^{RB_{\max}} P_{i-1,j}b_{i-1,j,0}, \\
\quad 1 \le i \le BS_{\max}-1, \\
b_{BS_{\max},0,k} = b_{BS_{\max},0,k+1} \\
\quad + \dfrac{p_c}{W_{BS_{\max}}}\left[\displaystyle\sum_{j=0}^{RB_{\max}} P_{BS_{\max}-1,j}b_{BS_{\max}-1,j,0} + P_{BS_{\max},0}b_{BS_{\max},0,0}\right], \\
\quad 0 \le k \le W_{BS_{\max}} - 2, \\
b_{BS_{\max},0,W_{BS_{\max}}-1} \\
\quad = \dfrac{p_c}{W_{BS_{\max}}}\left[\displaystyle\sum_{j=0}^{RB_{\max}} P_{BS_{\max}-1,j}b_{BS_{\max}-1,j,0} + P_{BS_{\max},0}b_{BS_{\max},0,0}\right].
\end{cases}
\tag{7}
$$

Via algebraic manipulation of Eq. (7), we can obtain

$$
\begin{cases}
b_{i,j,k} = \dfrac{W_i - k}{W_i}b_{i,j,0}, \\
\quad 0 \le i \le BS_{\max}-1,\ 0 \le j \le RB_{\max},\ 0 \le k \le W_i - 1, \\
b_{i,j,0} = \displaystyle\prod_{r=0}^{j-1}(1-P_{i,r})b_{i,0,0}, \\
\quad 0 \le i \le BS_{\max}-1,\ 1 \le j \le RB_{\max}, \\
b_{i,0,0} = \displaystyle\prod_{m=0}^{i-1}\left(p_c\sum_{r=0}^{RB_{\max}} P_{m,r}\prod_{s=-1}^{r-1}(1-P_{m,s})\right)b_{0,0,0}, \\
\quad 1 \le i \le BS_{\max},
\end{cases}
\tag{8}
$$

where $P_{i,-1}$ is set to be zero. Also from Eq. (8), $b_{i,j,k}$ can be obtained in terms of $b_{0,0,0}$, permission probability $P_{i,j}$, and collision probability p_c, by

$$
b_{i,j,k} = \frac{W_0 2^i - k}{W_0 2^i}\prod_{h=-1}^{j-1}(1-P_{i,h}) \prod_{m=-1}^{i-1}\left[p_c\sum_{r=0}^{RB_{\max}} P_{m,r}\prod_{s=-1}^{r-1}(1-P_{m,s})\right]b_{0,0,0}, \tag{9}
$$

where $P_{-1,j}$ is defined to be 1. By using the normalization condition for stationary state probabilities, the $b_{0,0,0}$ can be yielded as

$$
b_{0,0,0} = \frac{1}{\displaystyle\sum_{i=0}^{BS_{\max}}\sum_{j=0}^{RB_{\max}}\sum_{k=0}^{W_i-1}\frac{W_0 2^i - k}{W_0 2^i}\prod_{h=-1}^{j-1}(1-P_{i,h}) \prod_{m=-1}^{i-1}\left[p_c\sum_{r=0}^{RB_{\max}} P_{m,r}\prod_{s=-1}^{r-1}(1-P_{m,s})\right]}. \tag{10}
$$

Afterwards, the transmission probability of a station, p_τ, can be derived as

$$
\begin{aligned}
p_\tau &= \sum_{i=0}^{BS_{\max}}\sum_{j=0}^{RB_{\max}} P_{i,j}b_{i,j,0} \\
&= \sum_{i=0}^{BS_{\max}}\sum_{j=0}^{RB_{\max}}\left\{P_{i,j}\prod_{n=-1}^{j-1}(1-P_{i,n})\prod_{m=-1}^{i-1}\left[p_c\sum_{r=0}^{RB_{\max}} P_{m,r}\prod_{s=-1}^{r-1}(1-P_{m,s})\right]\right\}b_{0,0,0},
\end{aligned}
\tag{11}
$$

and the collision probability of station, p_c, is given by

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

• *System Throughput*

For the derivation of system throughput, we consider that the time span is partitioned into three categories: the idle slot time, denoted by T_σ, the successful transmission time, denoted by T_s, and the collision time, denoted by T_c. Proportionally, the idle slot time would be with a portion of $(1-P_{tr})$, the successful transmission time would be with a portion $P_{tr}P_s$, and the collision time would be with a portion of $P_{tr}(1-P_s)$. The P_{tr} is the probability of that at least one transmission occurs in a slot time, and it is given by

$$
P_{tr} = 1 - (1-p_\tau)^n. \tag{13}
$$

The P_s is the probability of that a successful transmission occurs, conditioned on the fact that at least one station transmits, and accordingly,

$$
P_s = \frac{np_\tau(1-p_\tau)^{n-1}}{P_{tr}}. \tag{14}
$$

Therefore, for a successful transmission of a packet in time T_s, the system throughput, denoted by S, can be obtained by

$$
S = \frac{P_{tr}P_s B}{(1-P_{tr})T_\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}, \tag{15}
$$

where the denominator denotes the average time interval taken for this successful transmission, and B is the average payload size of a packet.

Values of T_s and T_c are given by, if the basic access mechanism is adopted,

$$\begin{cases} T_s = H + B_t + SIFS + \delta + ACK + DIFS + \delta, \\ T_c = H + B_t + \delta + DIFS, \end{cases} \quad (16)$$

where H is the time required to transmit PHY and MAC frame headers; B_t is the average time that a payload is transmitted; SIFS is the duration of SIFS; δ is the propagation delay; ACK is the time required to transmit the acknowledgement packet; and DIFS is the duration of DIFS. They are given by, if the RTS/CTS access mechanism is used,

$$\begin{cases} T_s = RTS + SIFS + \delta + CTS + SIFS + \delta \\ \quad + H + B_t + SIFS + \delta + ACK + DIFS + \delta, \\ T_c = RTS + DIFS + \delta. \end{cases} \quad (17)$$

Note that collision is assumed to be occurred at RTS frame transmitted.

• *Delay*

As those described for Eq. (15), the average time interval taken for a successful transmission of a packet is $(1 - P_{tr})T_\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c$, and its probability is $P_{tr}P_s$. If the n contending stations are identical, the average delay of a station, denoted by T_D, can be obtained by

$$T_D = \frac{n \times [(1-P_{tr})T_\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c]}{P_{tr}P_s}. \quad (18)$$

• *The Optimal Value of* P_0

In WLAN, the number of stations n is not a directly controllable variable. The way to achieve optimal performance is to employ adaptive techniques to tune the value of W_0 based on an estimated value of n [6]. Bianchi stated in [6] that the maximum system throughput can be achieved if the optimal initial contention window in BEB, denoted by W_{opt}, is given by

$$W_{opt} \approx n\sqrt{2T_c/\sigma}. \quad (19)$$

In contrast, the initial contention window of the APP MAC scheme since is equivalent to W_0/P_0, the optimal value of P_0, denoted by P_0^*, can be obtained by

$$P_0^* = W_0/W_{opt} \approx W_0/n\sqrt{2T_c/\sigma}. \quad (20)$$

5. Numerical and Simulation Results

Table 1 lists system parameters of a considered WLAN environment and values of PHY-related parameters, which are referred to specifications of IEEE 802.11 [1]. In the simulations, we compare the APP scheme with the BEB and the DDFC [3] schemes. In the BEB scheme, two initial contention windows, W_0=16 and W_0=32, are assumed. In the DDFC scheme, the setting parameters are t_0=100 ms, t_s=10 ms and W_0=16. Since stations are operated in a saturation condition and the queueing time is not considered in the simulation, the packet waiting time by the DDFC scheme is accounted from the beginning of packet contention, not as the primary usage defined in [3]. In the following figures, results of APP are shown by numerical and/or simulation, while results of BEB and DDFC are given by simulation.

Table 1 Parameter settings for a WLAN environment.

Slot Time, σ	20 μs
DIFS	60 μs
SIFS	10 μs
Propagation Delay	1 μs
Bit Rate	11 Mbps
PHY Overhead	192 μs
MAC Header	28 byte
ACK Length	14 byte
Data Packet Payload, B	1028 byte
Max Backoff Stage, BS_{max}	4
Initial Contention Window, W_0	16
Transmission Retry Limit	∞

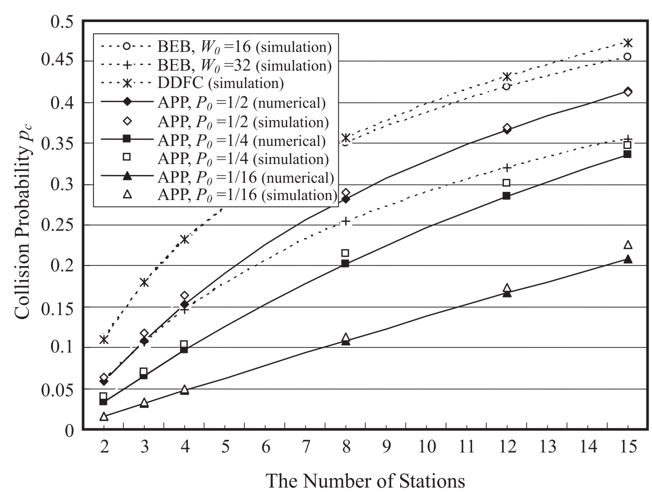

Fig. 2 Collision probabilities of APP, BEB, and DDFC.

Figure 2 illustrates the collision probability p_c of the APP, BEB, and DDFC MAC schemes. It reveals that APP with P_0=1/4 achieves an improvement of collision probability by 40% (38.8%) over DDFC (BEB with W_0=16), when the number of stations is 8. The reason is that the proposed APP MAC scheme assigns every packet a permission probability $\boldsymbol{P}$. When two stations count to zero simultaneously, the collision probability of APP is equal to $\boldsymbol{P}^2$. Thus, APP has smallest collision probability; and the smaller the P_0 is, the lower the collision probability would be. This phenomenon is equivalent to making the initial contention window larger. The figure also exhibits that the discrepancy between numerical and simulation results is less than 3.5%, thus this corroborates the collision probability analysis.

Figure 3 depicts the system throughputs of the APP, BEB, and DDFC MAC schemes. It can be seen that the throughput increases first and then decreases. It is because increasing the number of stations not only raises the chan-

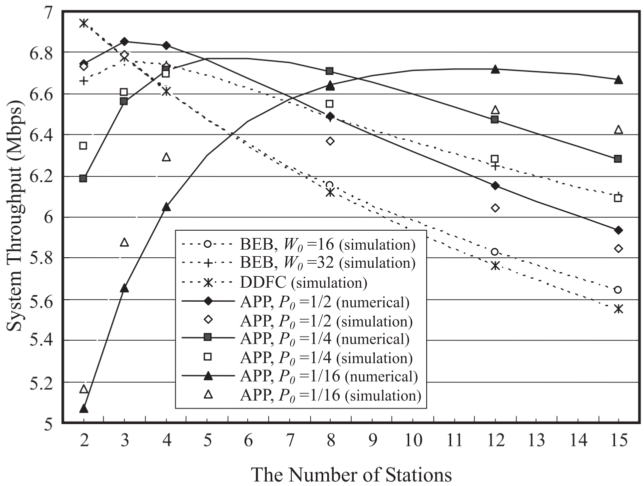

Fig. 3 System throughputs of APP, BEB, and DDFC.

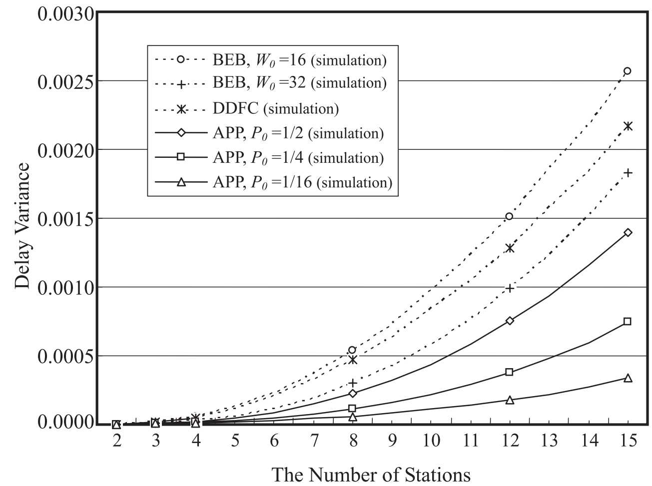

Fig. 5 Delay variances of APP, BEB, and DDFC.

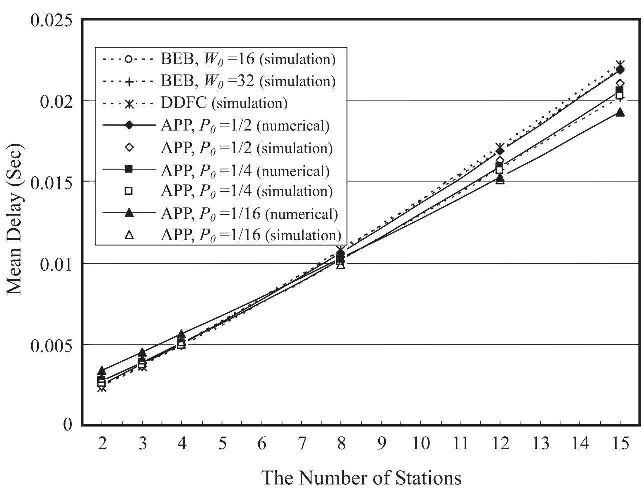

Fig. 4 Mean delays of APP, BEB, and DDFC.

nel utilization but also enlarges the packet collision probability as shown in Fig. 2, so the throughput increases first and it decreases due to high collision probability. Also, APP with P_0=1/4 achieves an improvement of throughput by 7% (6.5%) over DDFC (BEB with W_0=16) when the number of stations is 8. The reason is that APP can reduce the collision probability and increase the transmission efficiency consequently. It can also be found that the smaller P_0 will cause a lower system throughput when fewer stations are in the system. It is because the smaller P_0 is equal to making a larger initial contention window. This will increase the channel idle time and decrease the channel utilization. Noticeably, the difference between numerical and simulation results is also less than 3.5%, this justifying the validity of the throughout analysis.

Figure 4 shows the mean delays of the APP, BEB, and DDFC MAC schemes. It indicates that the APP with P_0=1/4 achieves an improvement of mean delay by 6.6% (6.1%) over DDFC (BEB with W_0=16), when the number of stations is 8. It is because the APP enhances the channel utilization. It can also be found that the smaller P_0 has a larger delay time when there are fewer stations in the system but a smaller delay time when there are more stations in the system. Also, the difference between numerical and simulation results is less than 3.23%, and this substantiates the delay analysis.

Figure 5 shows delay variances of the APP, BEB, and DDFC MAC schemes versus the number of stations by simulations. It can be found that the APP MAC scheme possesses the lowest delay variation, while the BEB MAC scheme (BEB with W_0=16) the highest. For example, the APP with P_0=1/4 achieves improvement of delay variation over DDFC (BEB with W_0=16) by 76.4% (79.4%), at the number of stations is 8. Also, the smaller the P_0 is, the more the improvement of delay variation would be. The reason is the proposed APP scheme adaptively determines the permission probability of transmission according to a function of the number of retransmission (***RT***) and the number of re-backoff (***RB***). The APP scheme lets the ready packet with the longest delay time transmit first and delays the new packet, this makes the delay time of packet be close to the mean value.

Besides, making P_0 smaller is equivalent to making the W_0 larger, thus lower collision probability. However, the large W_0 in the BEB cannot greatly decrease delay variance and it would cause the system performance degrade (see BEB with W_0=32 in Figs. 2–4). It is because the APP scheme is not actually increase the size of W_0, but provides another dimension (permission probability ***P***) to avoid collision and makes the transmission efficiency, thus the APP scheme has the smallest mean delay and highest system throughput.

Figure 6 shows the system throughput and delay variance of APP with optimal P_0^* and BEB with W_{opt} given in [6] by simulations, where the BEB operates with W_{opt} to obtain the maximum system throughput and the APP uses the optimal P_0 with fixed W_0. It can be found that APP with optimal P_0^* loses the system throughput by 1.3% but

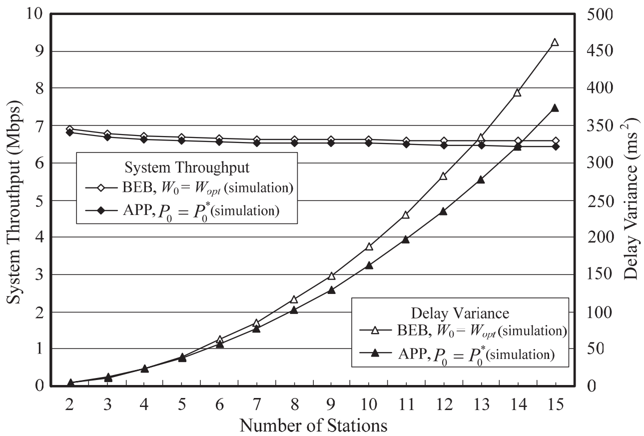

Fig. 6 Performance of APP with optimal P_0^* and BEB with W_{opt}.

gains an improvement of delay variation by 15%, compared to BEB with W_{opt}. This shows that the APP MAC scheme can achieve maximum system throughput and support good delay fairness.

6. Concluding Remarks

This paper proposed and analyzed an adaptive p-persistent (APP) MAC scheme for IEEE 802.11 WLAN to achieve fairness in the sense of low delay variance. The APP MAC scheme resolves the fairness problem at each access of stations by adaptively determining the permission probability of station according to the state of packet transmission of the station. It differentiates the permission probabilities of stations with various waiting delay, and assigns a higher priority (probability) to stations with larger packet delay. The paper analyzes the APP MAC scheme by Markov-chain model and successfully obtains the collision probability, the system throughput, and the mean delay. Results show that the discrepancy between the numerical results and the simulation results is very small, and the analyses are quite correct. Besides, the APP MAC scheme can effectively reduce the delay variance and enhance the system throughput.

The initial permission probability P_0 is an important design parameter in the APP MAC scheme. It can be determined by considering the system design objective which is to reduce the delay variance or enhance the system throughput. Besides, the initial permission probability P_0 can be adaptively determined according to the system load. For example, P_0 could be set to be 1/16 (1/2) when the system is in heavy (light) load.

Acknowledgement

The authors would give thanks to anonymous reviewer for their suggestions and corrections which help to improve the presentation and quality of the paper.

References

[1] IEEE Std 802.11b-1999, IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band.
[2] V. Bharghavan, A. Demers, S. Shenker, and L, Zhang, "MACAW: A media access protocol for wireless LANs," Proc. ACM SIGCOMM'94, pp.212–225, 1994.
[3] H. Yamada, H. Morikawa, and T. Aoyama, "Decentralized control mechanism suppressing delay fluctuation in wireless LANs," Proc. VTC 2003 Fall 2, pp.801–805, 2003.
[4] C.M. Yen, C.J. Chang, and Y.S. Chen, "An adaptive p-persistent MAC scheme for multimedia WLAN," IEEE Commun. Lett., vol.10, no.11, pp.737–739, 2006.
[5] C.J. Chang, F.Z.M. Yen, Y.S. Chen, and C.Y. Huang, "A novel adaptive p-persistent MAC scheme for WLAN providing low delay variance," ICC 2006, pp.3639–3644, 2006.
[6] G. Bianchi, "Performance analysis of IEEE 802.11 distributed coordination function," IEEE J. Sel. Areas Commun., vol.18, no.3, pp.535–547, 2000.
[7] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: Throughput and delay analysis," Comput. Commun., vol.25, no.3, pp.313–321, 2002.
[8] Y. Xiao, "A simple and effective priority scheme for IEEE 802.11," IEEE Commun. Lett., vol.7, no.2, pp.70–72, 2003.
[9] R.G. Cheng, C.J. Chang, C.Y. Shih, and Y.S. Chen, "A new scheme to achieve weighted fairness for WLAN supporting multimedia services," IEEE Trans. Wirel. Commun., vol.5, no.5, pp.1095–1102, 2006.

Chih-Ming Yen is a Ph.D. student in department of communication engineering from National Chiao Tung University, Hsinchu, Taiwan. His interest area includes wireless networks, mobile communications, high-speed networks, communications protocol design, and network performance evaluation. He is currently focusing the research areas on resource management for OFDM system. His research interests include radio resource management and wireless communication.

Chung-Ju Chang was born in Taiwan, ROC, in August 1950. He received the B.E. and M.E. degrees in electronics engineering from National Chiao Tung University, Hsinchu, Taiwan, in 1972 and 1976, respectively, and the Ph.D. degree in electrical engineering from National Taiwan University, Taiwan, in 1985. From 1976 to 1988, he was with Telecommunication Laboratories, Directorate General of Telecommunications, Ministry of Communications, Taiwan, as a Design Engineer, Supervisor, Project Manager, and then Division Director. He also acted as a Science and Technical Advisor for the Minister of the Ministry of Communications from 1987 to 1989. In 1988, he joined the Faculty of the Department of Communication Engineering, College of Electrical Engineering and Computer Science, National Chiao Tung University, as an Associate Professor. He has been a Professor since 1993. He was Director of the Institute of Communication Engineering from August 1993 to July 1995, Chairman of Department of Communication Engineering from August 1999 to July 2001, and Dean of the Research and Development Office from August 2002 to July 2004. Also, he was an Advisor for the Ministry of Education to promote the education of communication science and technologies for colleges and universities in Taiwan during 1995 V 1999. He is acting as a Committee Member of the Telecommunication Deliberate Body, Taiwan. Moreover, he serves as Editor for IEEE Communications Magazine and Associate Editor for IEEE Transactions Vehicular Technology. His research interests include performance evaluation, radio resources management for wireless communication networks, and traffic control for broadband networks. Dr. Chang is a member of the Chinese Institute of Engineers (CIE).

Yih-Shen Chen was born inMiaoli, Taiwan, R.O.C., in September 1973. He received the B.E., M.E., and Ph.D. degrees in communication engineering from National Chiao Tung University, Hsinchu, Taiwan, in 1995, 1997, and 2004, respectively. From 1997 to 1999, he was an Engineer with the Protocol Design Technology Department, Computer and Communications Research Laboratories, Industrial Technology Research Institute, Taiwan, where he was involved in the designing of software protocol for the DECT networks. Currently, he is with Sunplus Technology Company Ltd., Hsinchu, Taiwan, where he is developing an HSDPA system. His research interests include performance analysis, protocol design, and mobile radio networks.

ChingYao Huang received the B.S. degree in physics from National Taiwan University, Taipei, Taiwan, R.O.C., in 1987, the M.S. degree in electrical and computer engineering from the New Jersey Institute of Technology (NJIT), Newark, NJ, in 1991, and the Ph.D. degree in electrical and computer engineering from Rutgers University (WINLAB), Newark, NJ, in 1996. He joined AT&T, Whippany, NJ, and then Lucent Technologies in 1995, and was a system engineer (Member of Technical Staff) for AMPS/PCS Base Station System Engineering Department until 2002. In 2001 and 2002, he was an Adjunct Professor at Rutgers University and NJIT. In 2002, he joined the Electronic Engineering Department, National Chiao Tung University, Hsinchu, Taiwan, R.O.C., as an Assistant Professor. His research areas include wireless medium access controls, radio resource management, scheduler control algorithms for wireless high-speed data systems, end-to-end performance, and provisioning strategies. He has published more than 50 technical memorandums, journal papers, and conference papers and is a chapter author of the book *Handbook of CDMA System Design, Engineering and Optimization*. Currently, he has five U.S. and International patents and 14 pending patents. Dr. Huang has been actively involved with IEEE conferences, Wireless and Optical Communications Conference and Multi-Media and Networking Technologies Conference, where he has served as an organizer, planning committee member and session chair. He has also served multiple positions, including member of executive committee and the board director of the Chinese Institute of Engineers of Great New York Chapter (CIE-GNYC).