Difference Analysis in IEEE 802.11 DCF

Daisuke Umehara*, Hidekazu Murata†, and Satoshi Denno‡
*Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan
E-mail: umehara@kit.ac.jp
†Graduate School of Informatics, Kyoto University, Kyoto, Japan
‡Graduate School of Natural Science and Technology, Okayama University, Okayama, Japan

***Abstract*—In this paper, a simple and accurate estimation on performance of the original IEEE 802.11 distributed coordination function (DCF) is presented. The performances obtained from the Bianchi's analytical model of the IEEE 802.11 DCF are compensated by means of (1) the number of consecutive successful transmissions and (2) the deferred slot time. The compensated performances including throughput, packet loss rate, and the average number of transmissions approximate to the simulation results with a high degree of accuracy under a number of conditions even when the minimum contention window is small. The analytical and simulation results show us the possibility of performance improvement by the sender priority.**

I. Introduction

IEEE 802.11 distributed coordination function (DCF) is a carrier-sense based medium access control (MAC) protocol defined by IEEE 802.11 standards [1] and has been widely used in wireless local area networks (WLANs). Bianchi developed a simple and accurate analytical model of 802.11 DCF by means of two-dimensional Markov chain, the state of which is composed of the backoff stage and backoff counter [2]. Wu *et al.* incorporated any finite retry limit into the Bianchi's analytical model, in which the retry limit was originally assumed to be infinite [3]. The Bianchi's model was intended to estimate the saturated throughput in WLANs, i.e. all stations (STAs) always have packets to be transmitted and was extended to unsaturated conditions. However, the current 802.11 DCF will be slightly different from the originally-defined 802.11 DCF so that the Bianchi's model should be compensated for the original 802.11 DCF such like parameter optimization proposed by Abeysekera *et al.* [4]. Especially when the minimum contention window $\mathrm{CW_{min}}$ is small, i.e. the sender has priority, the Bianchi's model will be inaccurate for the original 802.11 DCF.

In this paper, a simple and accurate estimation scheme on performances of the original 802.11 DCF is presented even when $\mathrm{CW_{min}}$ is small without modifying the Bianchi's Markov chain. The performances such as throughput, packet loss rate, and the average number of transmissions obtained from the Bianchi's model are compensated by means of (1) the number of consecutive successful transmissions and (2) the deferred slot time. The analytical and simulation results show us a high degree of accuracy in the compensated performances and the possibility of performance improvement by the sender priority.

II. Analytical Model of 802.11 DCF

Let us first briefly describe the binary slotted exponential backoff algorithm of the original 802.11 DCF. A new packet is immediately transmitted from a STA when any other packets do not stay in the transmission queue and the channel is sensed idle during DCF interframe space (DIFS). Otherwise, the STA determines a random backoff counter k following the uniform distribution on $[0, \mathrm{CW}]$, where CW is a contention window which is initially set at $\mathrm{CW_{min}}$. The positive counter k decreases by one with the predefined slot time σ elapsing when the channel is sensed idle and otherwise it is frozen during the sensed busy time. Notice that the positive counter k always decreases by one just after the slot time σ or the sensed busy time in the current 802.11 DCF and hence the successful sender has some priority in the original 802.11 DCF. The packet is transmitted at the beginning of a slot just when the counter k becomes 0. The CW is updated to $\min\{2(\mathrm{CW}+1)-1, \mathrm{CW_{max}}\}$ if the current transmission fails and the number of retransmissions is less than the predefined maximum r, where $\mathrm{CW_{max}} = 2^m(\mathrm{CW_{min}}+1)-1$ is the maximum contention window, m is the maximum backoff stage, and $r+1$ is the retry limit. Otherwise, CW is reset at $\mathrm{CW_{min}}$. Alternatively, the CW in the ith retransmission is set at $\mathrm{CW}_i = 2^{\lambda_i}(\mathrm{CW_{min}}+1)-1$ for $0 \le i \le r$, where λ_i is defined as $\min\{m, i\}$.

Single-hop WLANs with an access point (AP) and n STAs are considered in this paper. All STAs attempt to transmit packets to the AP and always have packets to be transmitted in the transmission queue, i.e. they are saturated. The AP does not have any packet to be transmitted to STAs, i.e. only uplink data flows from STAs to the AP are considered. It is assumed that bit errors by fading, thermal noise, and interference do not occur, i.e. the signal-to-noise ratio (SNR) is sufficiently high, the AP and STAs have a propagation delay of δ each other, and the capture effect does not occur, i.e. the AP cannot obtain any information just when a collision occurs.

A two-dimensional Markov chain was developed to estimate the performances of 802.11 DCF [2], [3]. The Markov chain describes the behavior of the 802.11 DCF backoff algorithm, and consists of states (i, k) and their state transitions where i and k are the number of retransmissions and backoff counter, respectively, for $0 \le i \le r-1$ and $0 \le k \le W_i - 1$, where $W_i = \mathrm{CW}_i + 1$. In the Bianchi's model, the collision probability p on the condition that a STA transmits a packet is assumed to be constant regardless of which STA transmits or what value the backoff stage is. The steady-state probability of a state (i, k) is denoted as $b(i, k)$. The transmission probability in a slot, $\tau_{\mathrm{tx}} = \tau$, is expressed as the sum of all states $b(i, 0)$ for $0 \le i \le r$ and is derived as

$$\tau = \frac{2}{1 + W\left[\sum_{i=0}^{\lambda_r-1}(2p)^i + (2p)^{\lambda_r}\sum_{i=0}^{r-\lambda_r-1}p^i\right]\Big/\sum_{i=0}^{r-1}p^i}, \qquad (1)$$

TABLE I
SIMULATION CHARACTERISTICS. THE MAC AND PHY LAYERS ARE BASED ON THE 802.11A STANDARD.

Characteristics	Value
The number of STAs, n	10
Access mode	Basic
PHY rate	6 Mbps
Data MSDU	1500 bytes
Propagation delay, δ	0.1 µs
Slot time, σ	9 µs
SIFS time, T_{sifs}	16 µs
DIFS time, T_{difs}	34 µs
Maximum backoff stage, m	6
ACK MPDU	14 bytes
ACK timeout	50 µs

MPDU — MAC protocol data unit

where $W = W_0$. The collision probability in a transmission, $p_{\text{col}} = p$, is expressed as $p = 1 - (1 - \tau)^{n-1}$. The values in τ and p are derived by solving these two different equations.

The busy time with a successful transmission is expressed as $T_{\text{suc}} = T_{\text{data}} + T_{\text{sifs}} + T_{\text{ack}} + T_{\text{difs}} + 2\delta$ in the basic access mode, where T_{data} is the average of data packet time, T_{ack} is the ACK packet time, T_{sifs} is the short IFS (SIFS) time, and T_{difs} is the DIFS time. The collision busy time of sensing STAs is expressed as $T_{\text{col}} = T_{\text{data}} + T_{\text{difs}} + \delta$ whereas the collision busy time of colliding STAs is expressed as $T_{\text{data}} + T_{\text{ato}}$, where T_{ato} is the ACK timeout interval. The basic access mode is straightforwardly extended to the RTS/CTS access mode where RTS and CTS stand for request-to-send and clear-to-send, respectively.

The performances of the current 802.11 DCF are estimated by the number of STAs n, the transmission probability in a slot τ, and busy/idle intervals. The probability of an empty slot is expressed as $P_\sigma = (1 - \tau)^n$. The probability of a successful transmission is expressed as $P_{\text{suc}} = n\tau(1-\tau)^{n-1}$. The probability of a collision is expressed as $P_{\text{col}} = 1 - P_\sigma - P_{\text{suc}}$. By the Bianchi's model, the throughput is expressed as

$$S = \frac{P_{\text{suc}} \cdot D}{P_\sigma \cdot \sigma + P_{\text{suc}} \cdot T_{\text{suc}} + P_{\text{col}} \cdot T_{\text{col}}}, \quad (2)$$

where D is the average of data MAC service data unit (MSDU) size. The collision busy time of colliding STAs will be ignored because other sensing STAs are a majority of STAs and it is longer than T_{col}. The packet loss rate in an arrival packet is expressed as $q_{\text{loss}} = p^{r+1}$ because the packet is discarded if the number of transmissions reaches the retry limit $r + 1$. The average number of transmissions in an arrival packet is expressed as $N_{\text{tx}} = (1 - p^{r+1})/(1 - p)$, which is useful to estimate the average of packet delay and energy consumption of transmissions.

The Monte Carlo simulations are conducted for the original 802.11 DCF. The simulation characteristics in this paper are defined as in Table I. In this paper, let us assume that m is equal to r. The MAC and PHY layers are based on the 802.11a standard. A simulation trial is terminated just after 5×10^6 packets are successfully received by the AP. The relative errors of the performances obtained from the Bianchi's model to the simulation results for given $\text{CW}_{\min} = 15$, 7, and 3 are illustrated in Table II. When $\text{CW}_{\min}$ is set at 3, the estimated

TABLE II
THE RELATIVE ERRORS OF THE ESTIMATED PERFORMANCES TO THE SIMULATION RESULTS.

$\text{CW}_{\min}$	S	q_{loss}	N_{tx}	τ_{tx}	p_{col}
15	−1.52%	−0.12%	3.49%	−2.19%	5.79%
7	−4.45%	12.42%	8.82%	−5.07%	10.29%
3	−10.48%	40.04%	19.90%	−10.35%	16.99%

throughput S is 10% lower, the estimated packet loss rate q_{loss} is 40% higher, and the estimated number of transmissions N_{tx} is 20% higher than the simulation results. As shown in Table II, the Bianchi's model has considerable differences with the simulation results especially when $\text{CW}_{\min}$ is small.

III. THROUGHPUT ESTIMATION OF ORIGINAL 802.11 DCF

A major difference in the backoff algorithm between the current and original 802.11 DCFs is whether the backoff counter decreases or not in the case that the STA detects a busy interval. Taking into consideration this discrepancy, two compensation schemes on performances of the original 802.11 DCF are proposed; one is based on the number of consecutive successful transmissions and the other is the deferred slot time.

A. Number of Consecutive Successful Transmissions

Let us consider the case that a STA succeeds in transmitting a packet to the AP as shown in Fig. 1. The positive backoff counters of the other STAs are frozen in the original 802.11 DCF, i.e. their value k remains at the beginning of the next contention period. The successful STA determines a next backoff counter following a uniform random variable on $[0, \text{CW}_{\min}]$. If the STA obtains the backoff counter of 0 with a probability of $1/(\text{CW}_{\min} + 1) = 1/W$, it transmits the next packet after DIFS without contending because the other STAs have positive backoff counters. As a result, the STA succeeds in transmitting consecutive $(1 - 1/W)^{-1} = W/(W - 1)$ packets on average once a packet makes a successful transmission as in Fig. 1.

The $N_{\text{cst}} = W/(W - 1)$ consecutive successful transmissions were presented to achieve fairness between uplink and downlink data flows [4] and are exploited to compensate the throughput in this paper. The compensated throughput is derived as

$$S = \frac{W \cdot P_{\text{suc}} \cdot D}{W \cdot P_{\text{suc}} \cdot T_{\text{suc}} + (W - 1)(P_\sigma \cdot \sigma + P_{\text{col}} \cdot T_{\text{col}})}, \quad (3)$$

by substituting $N_{\text{cst}} \cdot T_{\text{suc}}$ and $N_{\text{cst}} \cdot D$ for T_{suc} and D in (2), respectively. However, the throughput will be overestimated by compensating it with N_{cst} although the behavior with varying $\text{CW}_{\min}$ is similar to the simulation results. This argument points a need for some additional compensation in order to achieve a further accurate approximation.

B. Deferred Slot Time

Let us consider the backoff counter k of a deferred STA after a busy interval as shown in Fig. 2. The positive backoff counter k stays in the next slot time σ and the deferred STAs will be a majority of STAs as compared with the successful STA or the colliding STAs particularly when the number of STAs is large. Therefore, it will be effective to add the deferred slot

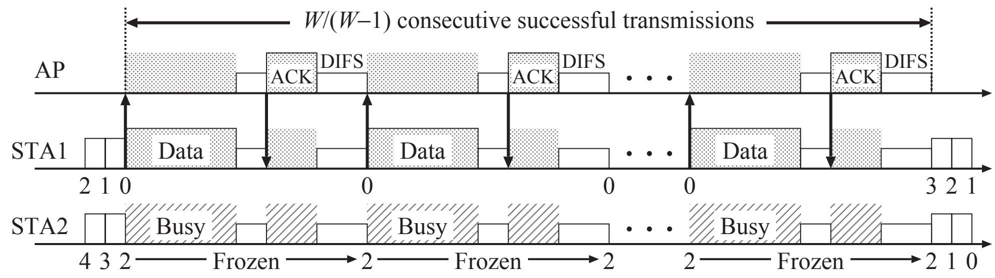

Fig. 1. An example of consecutive successful transmissions.

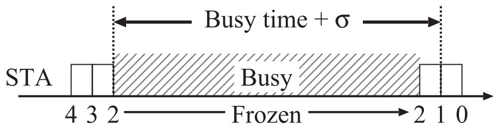

Fig. 2. The interval with the same backoff counter for a deferred STA.

TABLE III
THE RELATIVE ERRORS OF THE COMPENSATED PERFORMANCES TO THE SIMULATION RESULTS.

CW_{min}	S	q_{loss}	N_{tx}	τ_{tx}	p_{col}
15	−0.49%	−6.35%	1.01%	1.57%	1.65%
7	−1.14%	−1.55%	2.50%	1.34%	2.77%
3	−1.46%	5.67%	4.43%	0.65%	2.87%

time σ to the prior busy time. The compensated throughput is derived as

$$S = \frac{W \cdot P_{suc} \cdot D}{W \cdot P_{suc} \cdot T_{suc} + (W-1)(\sigma + P_{col} \cdot T_{col})}, \quad (4)$$

by substituting $N_{cst} \cdot T_{suc} + \sigma$ and $T_{col} + \sigma$ for $N_{cst} \cdot T_{suc}$ and T_{col} in (3), respectively. Equation (4) provides a further accurate estimation on throughput of the original 802.11 DCF without modifying the Bianchi's Markov chain.

C. Estimation on Other Performances

The compensation by the average number of consecutive successful transmissions, N_{cst}, is exploited to obtain the other performances with a high degree of accuracy.

The packet loss rate in an arrival packet is expressed as

$$q_{loss} = \frac{(W-1)p^{r+1}}{W - p^{r+1}}. \quad (5)$$

The average number of transmissions in an arrival packet is expressed as

$$N_{tx} = \frac{(W-p)(1-p^{r+1})}{W(1-p)} + \frac{(r+1)p^{r+1}}{W}. \quad (6)$$

The transmission probability in a slot is expressed as

$$\tau_{tx} = \frac{(W-p)\tau}{W-1+(1-p)\tau}. \quad (7)$$

The collision probability in a transmission is expressed as

$$p_{col} = \frac{(W-1)p}{W-p}. \quad (8)$$

D. Numerical Results

The relative errors of the compensated performances are illustrated in Table III under the same conditions of Table II in section II. It is found that all parameters except q_{loss} in $CW_{min} = 15$ are improved as compared with Table II. In particular, the relative error of the throughput S in $CW_{min} = 3$ becomes substantially accurate from −10.48% to −1.46%. The original 802.11 DCF has the priority on successful sender so that the results show us the possibility of performance improvement by the sender priority.

IV. CONCLUSION

In this paper, a simple and accurate estimation scheme on performances of the original IEEE 802.11 DCF has been presented without modifying the Bianchi's Markov chain. The performances obtained from the Bianchi's model are compensated by means of the number of consecutive successful transmissions and the deferred slot time. It has been shown that the compensated performances including throughput, packet loss rate, and the average number of transmissions approximate to the simulation results with a high degree of accuracy under a number of conditions even when the minimum contention window is small. The analytical and simulation results have shown us the possibility of performance improvement by the sender priority.

ACKNOWLEDGMENT

The work was supported by the Strategic Information and Communications R&D Promotion Programme (SCOPE) of the Ministry of Internal Affairs and Communications, Japan.

REFERENCES

[1] IEEE Std 802.11-2012, *Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications*, IEEE Std. 802.11-2012, 2012.

[2] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[3] H. Wu, Y. Peng, K. Long, S. Cheng, and J. Ma, "Performance of reliable transport protocol over IEEE 802.11 wireless LAN: Analysis and enhancement," in *Proc. IEEE INFOCOM 2002*, New York, NY, USA, Jun. 2002, pp. 599–607.

[4] B. A. H. S. Abeysekera, T. Matsuda, and T. Takine, "Dynamic contention window control mechanism to achieve fairness between uplink and downlink flows in IEEE 802.11 wireless LANs," *IEEE Trans. Wireless Commun.*, vol. 7, no. 9, pp. 3517–3525, Sep. 2008.