IEEE 802.11 프로토콜에서 두 DCF 방식의 성능 비교

정회원 박 철 근*

Performance Comparisons of Two DCF Methods in the IEEE 802.11 Protocol

Chul-Geun Park* *Regular Member*

요 약

최근 무선 LAN의 인기로 IEEE 802.11 프로토콜의 성능 분석과 개선에 많은 관심이 생겨났다. 본 논문에서는 도착하는 패킷의 크기가 일반 확률분포를 가질 때 MAC 계층 패킷 서비스 시간을 조사하여 IEEE 802.11 프로토콜의 두 가지 매체 접속 방식을 분석한다. 무선 LAN에서 IEEE 802.11 프로토콜의 수율 및 지연 성능을 분석하기 위해 M/G/1/K 큐잉 모델을 사용한다. 두 가지 접속 방법, 기본 접속과 RTS/CTS 접속 방식의 성능을 비교한다. 그리고 시스템의 수율 및 평균 패킷 지연과 패킷 블록킹 확률을 포함하여 큐의 동작 상태를 보기 위한 여러 가지 수치예를 보여준다.

Key Words : WLAN, 패킷지연, 수율, 큐잉모델, 성능분석

ABSTRACT

In recent year, the popularity of WLAN has generated much interests on improvement and performance analysis of the IEEE 802.11 protocol. In this paper, we analyze two medium access methods of the IEEE 802.11 MAC protocol by investigating the MAC layer packet service times when arrival packet sizes have a general probability distribution. We use the M/G/1/K queueing model to analyze the throughput and the delay performance of IEEE 802.11 MAC protocol in a wireless LAN. We compare the performances of Basic access method and RTS/CTS access method. We take some numerical examples for the system throughput and the queue dynamics including the mean packet delay and packet blocking probability.

Ⅰ. Introduction

The IEEE 802.11 protocol defines the MAC (Medium Access Control) and the physical layer functions of WLANs(Wireless LANs). The MAC protocol employs 2 medium access methods for packet transmission which are the DCF (Dis- tributed Coordination Function) and the PCF(Point Coordination Function)[1]. We focus on the DCF scheme which is widely developed in the com- mercial uses. The mandatory DCF of the MAC protocol provides a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) and suits delay insensitive traffic. The optional PCF based on the contention free service is built on the top of the DCF and is suitable for delay sensitive traffic[2,3].

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* 선문대학교 정보통신공학부 (cgpark@sunmoon.ac.kr)
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The DCF defines 2 methods for transmitting data packets, namely, the Basic method and the RTS/CTS (Request-To-Send/Clear-To-Send) access method[4]. In Basic access method, a station senses the channel idle for a specific time interval. If the channel is idle, the station transmits data packet. If the channel is busy, to minimize collisions, the station defer its transmission attempts to a later time on the basis of a backoff algorithm[1,4]. On the occasion that the collision probability is high and packet size is larger than a threshold, the RTS/CTS method is used. In this case, short RTS and CTS packets are exchanged to reserve the medium prior to the transmission duration and copes with hidden stations[5].

A large amount of works on the IEEE 802.11 protocol has been studied for the saturation throughput and delay analysis of CSMA/CA[3-8]. The 2-dimensional MC(Markov Chain) model introduced by Bianchi[6] for the analysis of saturation throughput has become a common method to study the performance of the IEEE 802.11 MAC protocol[4]. Most of the previous studies[3-8] dealt with the throughput and delay analysis of IEEE 802.11 MAC layer in saturation conditions. The MAC delay analysis of the current works except [5] has been limited to the derivation of mean value while the higher moments and the probability distribution function of the delay are untouched.

Fortunately, in [5], they had maid a study on throughput and delay of IEEE 802.11 MAC protocol by obtaining the MAC layer packet service time, when the arrival packets to each station has a uniform probability distribution. But we know well that the trimodal packet size distribution has been demonstrated in subscriber access networks[9,10]. Hence we can catch an idea that the size of arrival packets have a general distribution. In this paper, we compare the performances of two DCF access methods by investigating the M/G/1/K queueing model of a wireless station on the basis of the generally distributed MAC layer packet service time.

The rest of this paper is organized as follows. In Section 2, we provide an overview of the two DCF access methods including the backoff algorithm. Section 3 describes the probability distribution of the MAC layer service time when the size of arrival packets to each station has a general probability distribution. Section 4 describes the M/G/1/K model for a wireless station. In Section 5, we take some numerical examples for the queue dynamics including the mean packet delay and packet blocking probability. We finally draw conclusions in Section 6.

Ⅱ. System Model

The DCF based on the CSMA/CA provides two access methods for transmitting data packets. The essential method used in DCF is called Basic access method, which is depicted in Fig. 1. In the IEEE 802.11, three different IFS(Inter-frame Space) time intervals have been specified to provide various priority levels for access to the medium, namely, SIFS(Short IFS), PIFS(PCF IFS) and DIFS(DCF IFS). The SIFS is the smallest one followed by PIFS and DIFS. After a SIFS, only ACK(Acknowledgements), CTS and data packet may be sent. In order to minimize collisions, after an idle DIFS, a station is allowed to transmit only at the beginning of a slot time, which is equal to the time needed to any station to detect the transmission of a packet from any other station and is denoted by δ as a unit slot time[4,6].

The other way of transmitting data packets is called the RTS/CTS method[2,3], which is depicted

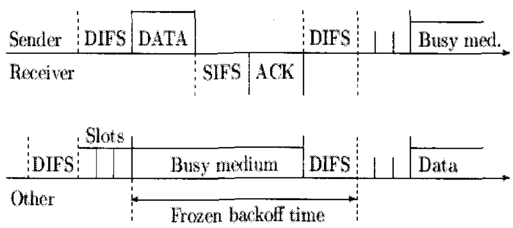

Fig. 1 Basic access mechanism

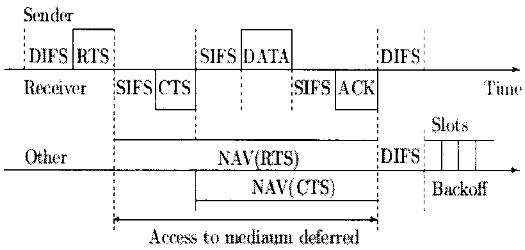

Fig. 2 RTS/CTS access mechanism

in Fig. 2. Two types of carrier sensing functions can be managed. The physical carrier sensing is done by detecting any channel activity on the physical layer by other stations. The virtual carrier sensing is provided by the NAV(Network Allocation Vector), which is a timer that indicates the amount of time the medium will be reserved. All stations that hear the data or RTS update their NAV field based on the value of duration field in the received packet which includes the SIFS and the ACK packet transmission following the data packet, before sensing the medium again.

When a packet arrives at the head of the transmission buffer, it will first monitor the channel activity. If the channel is busy, the MAC waits until the medium become idle, then defers for an extra time interval DIFS. If the channel stays idle during the DIFS deference, the MAC then starts the backoff process. The DCF uses a slotted binary exponential backoff technique.

To begin the backoff process, each station maintains a contention window CW, which takes $CW_{\min}$ as an initial value and doubles its value before it reaches a maximum upper limit $CW_{\max}$. The backoff counter is measured in terms of slot time. The backoff counter is uniformly chosen in the range of $[0, CW)$, where CW is the current contention window. If the channel becomes busy during a backoff process, the backoff is frozen.

When the channel becomes idle again and the backoff counter reaches zero, the station attempts to retransmit the packet. If the maximum transmission failure limit is reached, the retransmission shall stop, $CW_{\max}$ shall be reset to $CW_{\min}$ and the packet shall be discarded.

Ⅲ. The Distribution of the MAC Layer Packet Service Time

3.1 The MAC layer packet service time

The MAC layer packet service time is the time interval between the time instant that a packet starts to contend for transmission and the time instant that the packet either is acknowledged for correct reception by the intended receiver or is dropped. The MAC layer packet service depends on the number of active stations, the probability distribution of packet sizes and the number of retransmission attempts (backoff stages) based on the backoff mechanism of CSMA/CA.

The collision probability p_c is defined by the probability that there is at least one of other stations which will transmit at the same backoff time slot. We assume that this probability does not change and is independent during the transmission regardless of backoff stages. We also assume that packet sizes are generally distributed. Then the MAC service time is a non-negative random variable, which is denoted by T_B.

Let T_S be a random variable representing amount of time slots while channel is busy due to a successful transmission. Define $s_i = P(T_S = i)$, $i = 1, 2, \cdots$ as the probability distribution of T_S. Let T_C be a random variable representing amount of time slots while channel is busy due to collision. We define $c_i = P(T_C = i)$, $i = 1, 2, \cdots$ as the probabilities of T_C. Then the MAC layer packet service time T_B has a discrete probability of $b_i = P(T_B = i)$, $i = 1, 2, \cdots$. Obviously, the probability distribution $b_i, i = 1, 2, \cdots$ depends on the transmission rate, the length of the packet, and the specific medium access mechanism such as the basic access method and the RTS/CTS access method[5,6].

To find the PGF(Probability Generating Function) of T_B, let Y_p be a discrete random variable of packet sizes and let $a_i = P(Y_p = i)$, $i = 1, 2, \cdots, L_p$, where L_p is defined by the maximum packet length. We assume that this random variable is independently identically distributed(i.i.d) for all n active stations. Further we define $C(z), S(z)$ and $B(z)$ as the PGFs of the random variables T_C, T_S and T_C, respectively.

3.2 The processes of collision and successful transmission

We first consider Basic access method. As shown in Fig. 1, the successful transmission period T_S consists of DATA, ACK, SIFS and DIFS intervals. Let $l_1 = [(ACK+SIFS+DIFS)/\delta]+1$, where $[x]$ is the Gaussian integer. Then we have the PGF of the random variable T_S as follows

$$S(z) = \sum_{i=0}^{L_p} a_i z^{i+l_1}, \tag{1}$$

where a_i is the probability mass function for the packet size.

The collision period T_C consists of DATA, ACK, SIFS and DIFS intervals. In Basic access method, T_C is determined by the longest one of the collided packets. We assume that the probability of three or more packets simul- taneously colliding is neglected. Let Y_1 and Y_2 be two random variables of packet sizes engaged in collision, then its probability distribution can be calculated by

$$P(T_C = l_1 + i) = P(Y_1 = i, Y_2 \le i) + P(Y_2 = i, Y_1 \le i) - P(Y_1 = i, Y_2 = i).$$

Thus we can obtain the PGF of the random variable T_C as

$$C(z) = \sum_{i=0}^{L_p} [2a_i F_Y(i) - (a_i)^2] z^{i+l_1}, \tag{2}$$

where $F_Y(i)$ is the cumulative distribution function of $a_i, i = 1, 2, \cdots, L_p$.

Let us now consider the case that the RTS/CTS access method is used. As shown in Fig 2, the successful transmission period T_S consists of RTS, CTS, DATA, ACK, 3 SIFSs and DIFS. Let $l_2 = [(RTS+CTS+ACK+3SIFS+DIFS)/\delta]+1$, then we have the PGF of the random variable T_S as

$$S(z) = \sum_{i=0}^{L_p} a_i z^{i+l_2}. \tag{3}$$

Similarly, let $l_3 = [(RTS+SIFS+CTS+DIFS)/\delta]+1$ for the PGF of the collision period T_C, then we have the PGF as

$$C(z) = z^{l_3}. \tag{4}$$

3.3 Packet transmission probability and Markov chain

The backoff process decreases its counter by one for every idle slot. We let p_c be the collision probability seen by a packet being transmitted on the medium. Assume that there are n active stations in a wireless LAN and that packet arrival processes at all stations are i.i.d. Then we have

$$p_c = 1 - [1 - (1 - p_0)\tau]^{n-1} \tag{5}$$

where p_0 is the idle probability that there are no packets to transmit at the MAC layer of the considering station and τ is the packet trans- mission probability that the station transmits in a random slot given that the station has packets to transmit. Let p_s be the probability that there is one successful transmission among other $n-1$ stations in the considered slot given that the current station does not transmit. Then, by the equation (5), we have

$$p_s = (n-1)\left[(1-p_c)^{\frac{n-2}{n-1}} + p_c - 1\right].$$

To find the packet transmission probability, we let $W_0 = CW_{\min}$ and m be the maximum backoff stage such that $2^m W_0 = CW_{\max}$ and let $W_i = 2^i W_0$, where $i, 0 \le i \le m$, is called backoff stage. Let $s(t)$, $b(t)$ and $k(t)$ be the stochastic processes representing the backoff stage, the backoff counter and the frozen period of the station at a time slot t respectively. Then the 3-dimensional stochastic process $(s(t), b(t), k(t))$ forms a discrete time MC depicted in Fig. 3.

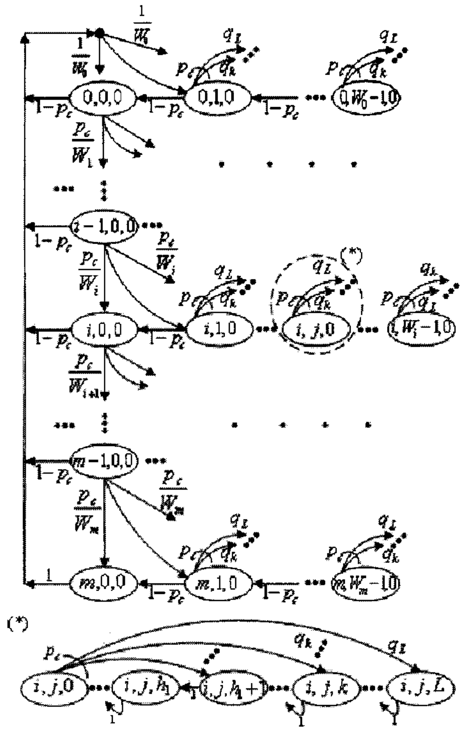

Fig. 3 State transition diagram of the discrete time Markov chain

At each transmission, the backoff counter is uniformly chosen in the range $(0, W_i)$, where i is the current backoff stage, i.e. the number of transmission failed for the considered packet. We denote the one-step transition probability of the process $(s(t), b(t), k(t))$ by

$$P((i_1, j_1, k_1)|(i_0, j_0, k_0)) = P((s(t+1) = i_1, b(t+1) = j_1, k(t+1) = k_1)|(s(t) = i_0, b(t) = j_0, k(t) = k_0)).$$

Then the one-step transition probabilities for backoff stages and backoff counters at the original state of the frozen period are summarized as, for $i = 0, 1, \cdots, m$,

$$P((i,j,0)|(i,j+1,0)) = 1-p_c, 0 \le j \le W_i - 2,$$
$$P((i,j,0)|(i-1,0,0)) = p_c/W_i, i \ne 0, 0 \le j \le W_i - 1,$$
$$P((0,j,0)|(i,0,0)) = \begin{cases} (1-p_c)/W_0, & i \ne m, 0 \le j \le W_i - 1, \\ 1/W_0, & i = m, 0 \le j \le W_i - 1. \end{cases}$$

The one-step transition probabilities of the frozen period at the backoff stage i and the backoff counter j are given by, for $i = 0, 1, \cdots, m$,

$$P((i,j,k-1)|(i,j,k)) = 1, 0 \le j \le W_i - 1, 0 < k \le L,$$
$$P((i,j,k)|(i,j,0)) = p_c q_k, 1 \le j \le W_i - 1, 0 < h_1 < k \le L,$$

where $L = h_1 + L_p$, and h_1 equals l_1(Basic) or l_2 (RTS/CTS). So we have $s_k = a_{k-h_1}, c_k = 2a_{k-h_1} \times F_Y(k-h_1) - a^2_{k-h_1}$, for Basic access method and $s_k = a_{k-h_1}$, $c_{l_3} = 1$ for RTS/CTS access method, and $k = h_1, \cdots, L$, by the definitions of T_S and T_C. Hence q_k, $k = h_1, \cdots, L$, is a distribution of the discrete random variable representing sum of packet size and some inter-frame spaces as follows

$$q_k = \frac{p_s}{p_c} s_k + \frac{p_c - p_s}{p_c} c_k. \qquad (6)$$

Let $b_{i,j,k} = \lim_{t \to \infty} P(s(t) = i, b(t) = j, k(t) = k)$, $0 \le i \le m$, $0 \le j \le W_i - 1$, $0 \le k \le L$ be the stationary distribution of the MC. Then, in steady state, we can derive the following relations from the state transition diagram. For $i = 0, \cdots, m$, $j = 1, \cdots, W_i - 1$, we have,

$$b_{i,j,k} = \begin{cases} p_c b_{i,j,0}, & 1 \le k \le h_1, \\ p_c b_{i,j,0} \sum_{l=k}^{L} q_l, & h_1 + 1 \le k \le L. \end{cases}$$

By the recursion, we have, for $i = 1, \cdots, m$

$$b_{i,0,0} = (p_c)^i b_{i,0,0},$$
$$b_{i,0,0} = (1-p_c) b_{i,1,0} + \frac{p_c}{W_i} b_{i-1,0,0},$$
$$b_{i,j,0} = \frac{W_i - j}{(1-p_c) W_i} b_{i,0,0}, 1 \le j \le W_i - 1.$$

By the normalization condition, we have

$$1 = \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} b_{i,j,0} + \sum_{i=0}^{m} \sum_{j=1}^{W_i - 1} \sum_{k=1}^{L} b_{i,j,k} + \sum_{i=0}^{m} b_{i,0,0}.$$

For simplicity, let $\eta = 1 + p_c \sum_{k=h_1+1}^{L} k q_k$, then we can refer to [9] for finding $b_{0,0,0}$ as

$$b_{0,0,0} = \left[\frac{\eta W_0 (1-(2p_c)^{m+1})}{2(1-p_c)(1-2p_c)} - \frac{\eta(1-p_c^{m+1})}{2(1-p_c)^2} + \frac{1-p_c^{m+1}}{1-p_c} \right]^{-1}.$$

When the backoff counter reaches zero, a station will attempt to transmit packet regardless of backoff stage. So we can find the probability τ

that the station which has a packet in its buffer transmits in a randomly chosen time slot. Thus we can refer to [10] for finding τ by

$$\tau=\left[\frac{\eta W_0(1-(2p_c)^{m+1})}{2(1-2p_c)(1-p_c^{m+1})}-\frac{\eta}{2(1-p_c)}+1\right]^{-1}.$$

3.4 The PGF of MAC layer packet service time

In this subsection, we obtain the PGF of the MAC layer packet service time. In the backoff process, if the medium is idle, the backoff counter has the probability $1-p_c$ to decrement by 1 during a time slot and the probability p_c to stay at the original state $(i,j,0)$ during the frozen period. Moreover the frozen period has the probability p_s to stay at the original state during T_S and has the probability p_c-p_s to stay at the original state during T_C. Let $H_b(z)$ be the PGF of time interval needed to decrement the backoff counter by 1, then the equation (6) gives

$$H_{b(z)}=\frac{(1-p_c)z}{1-p_c z\sum_{k=h_1+1}^{L}q_k z^k}.$$

By using the above equation, we can obtain the PGF of the MAC layer packet service time T_B, denoted as $B(z)$, which is represented by $S(z)$, $C(z)$ and $H_b(z)$ as

$$B(z)=(1-p_c)\,S(z)\sum_{i=0}^{m-1}(p_cC(z))^iH_i(z)+(p_cC(z))^mS(z)H_m(z),$$

where $S(z)$ and $C(z)$ are given in the equations (1)-(4) and $H_i(z)$ is defined by

$$H_i(z)=\prod_{j=0}^{i}\sum_{k=0}^{2^jW_0-1}\frac{1}{2^jW_0}(H_b(z))^k.$$

Ⅳ. Queueing Analysis

In this section we present the considered M/G/1/K queueing model with the arrival rate λ and the MAC layer packet service time to investigate throughput, packet blocking probability and mean packet delay. Let A_k be the probability of k packet arrivals during the MAC layer packet service time T_B, then we have

$$A_k=\sum_{t=1}^{\infty}e^{-\lambda t}\frac{(\lambda t)^k}{k!}P(T_B=t).$$

Let $X(t)$ be the number of packets in the buffer at time slot t. Let t_n be the n-th packet departure instant and let $X_n=X(t_n+)$ be the state of the queueing system just after t_n. Then the 1-step transition probability matrix $\tilde{P}$ is given by

$$\tilde{P}=\begin{pmatrix}A_0, A_1, A_2, \cdots, A_{K-2}, D_{K-1}\\ A_0, A_1, A_2, \cdots, A_{K-2}, D_{K-1}\\ 0 \;\; A_0 \;\; A_1 \;\cdots\; A_{K-3} \;\; D_{K-2}\\ \vdots \;\; \vdots \;\; \vdots \;\; \ddots \;\; \vdots \;\; \vdots\\ 0,\; 0,\; 0,\; \cdots,\; A_0,\; D_1\end{pmatrix}$$

where $D_k=\sum_{i=k}^{\infty}A_i$.

Let $\pi_k=\lim_{n\to\infty}P(X_n=k)$, then the steady-state probability $\pi=(\pi_k)$ is given by solving $\pi\tilde{P}=\pi$. Let $x_k=\lim_{t\to\infty}P(X(t)=k|X(0)=0)$ at an arbitrary time, then we have

$$x_n=\frac{\pi_n}{\pi_0+\rho}, 0\le n\le K-1,$$
$$x_K=1-\frac{1}{\pi_0+\rho},$$

where ρ is the traffic intensity and $\rho=\lambda E[T_B]$. The packet blocking probability P_B for an arbitrary packet is given by

$$P_B=x_K=1-\frac{1}{\pi_0+\rho}.$$

We can use Little's law with arrival rate λ to find the mean packet delay W,

$$\lambda(1-P_B)W=\sum_{k=0}^{K}kx_k.$$

We can easily obtain the throughput at each station in terms of P_B and p_c^{m+1} i.e., the packet discard probability due to transmission failures.

V. Numerical Results

In this section, we present some numerical results to show the PGF $B(z)$ for the MAC layer packet service time, the packet waiting time, packet blocking probability and the queue dynamics of the M/G/1/K model with the service time $B(z)$. We use the system parameters for FHSS(Frequency Hopping Spread Spectrum) PHY-specification and DCF access method[5].

In addition, the other parameters such as the channel bit rate 2Mbps, the number of active stations $n=10$, the maximum backoff stage $m=5$ and the initial value of a contention window $W_0=32$ are fixed. We assume that the propagation delay is neglected and the channel is error-free and all stations are awake all the time[3]. We also assume that three modes correspond to the most frequent packet sizes:64 bytes(47%), 594 bytes (15%) and 1518 bytes (28%). In addition, we consider the other packet sizes of 300 bytes(5%), 1300 bytes (5%)[11,12].

Fig.s 4 and 5 illustrate how the collision probability p_c has influence on the probability distribution of the MAC layer packet service time in the two respective cases of Basic access method and RTS/CTS access method. In these Fig.s, we can see that the 2-stage Erlangian distribution is a good approximation to the real distribution of the MAC layer packet service time.

In Fig. 4, we choose a lower collision $p_c=0.05$, which means that the considered station has the more successful packet transmission chance. We can see that the MAC service time of Basic access method is shorter than that of RTS/CTS access method. This is because RTS/CTS access method has longer mean length of T_S than Basic access method.

In Fig. 5, we choose a higher collision probability $p_c=0.4$ which means that the considered station has the less successful packet transmission chance. We can see that the MAC service time of Basic access method is longer than that of RTS/CTS access method. This is because RTS/CTS access method has shorter mean length of T_C than Basic access method.

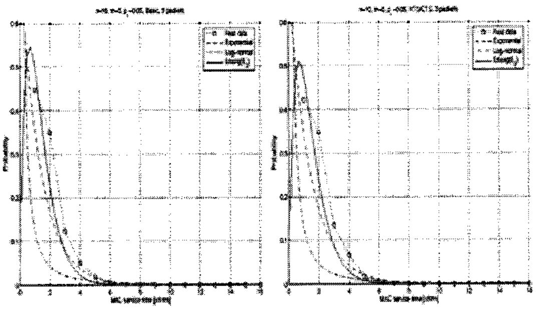

Fig. 4 PDFs :$B(z)$ (Bacic vs. RTS/CTS, $p_c=0.05$)

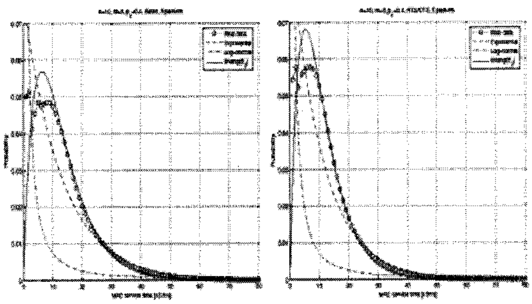

Fig. 5 PDFs :$B(z)$(Bacic vs. RTS/CTS, $p_c=0.4$)

Now we present some numerical result of the M/G/1/K model with a finite capacity buffer and the MAC layer service time $B(z)$. In this part, we deal with the performance comparison of Basic access and RTS/CTS access method.

Fig. 6 and 7 show the packet blocking probabilities and the mean packet waiting times of the both access methods when the arrival rate and the traffic intensity vary in three cases of collision probabilities $p_c=0.1,0.2,0.3$, respectively. Moreover, from the equation (9), we can see that Basic access

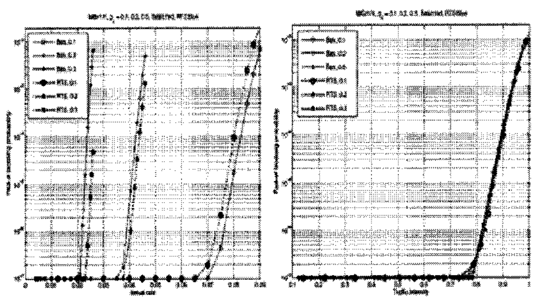

Fig. 6 Packet blocking probability w.r.t. λ and ρ

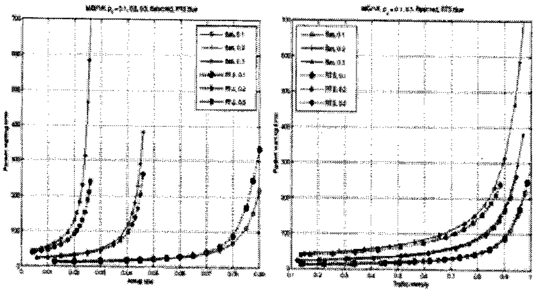

Fig. 7 Packet waiting time w.r.t. λ and ρ

method has the corresponding mean MAC service times $E[T_B]=10.36$, 20.569, 37.005 and RTS/CTS access has the corresponding mean MAC service times $E[T_B]=10.723$, 19.997, 33.477 for $p_c=0.1$, 0.2,0.3, respectively.

From the left figure of Fig. 6, we can see that the packet blocking probabilities have sharp changes around arrival rates $\lambda=0.022$, 0.036 and 0.07 in cases of $p_c=0.3,0.2,0.1$, respectively. This is because the collisions increase significantly around these traffic loads and increase rapidly as large as the collision probabilities are. But from the right one of Fig. 6, we can see that packet blocking probabilities have sharp changes around almost the same traffic intensity around $\rho=\lambda/E[T_B]=0.8$ in all cases of $p_c=0.1,0.2$ and 0.3.

From Fig. 7, we can see the similar results on the packet waiting times of both access methods when the arrival rate and the traffic intensity vary in three cases of collision probabilities $p_c=0.1,0.2$, 0.3 respectively. From these figures, we can also see that Basic access method has slight better performances than RTS/CTS access method when the collision probability is low($p_c=0.1$) and vice versa when the collision probability is high ($p_c=0.3$).

Fig. 8 and 9 show the throughput performance and the idle probability p_0 when the arrival rate and the traffic intensity vary. From the com- parison of two figures, we can see that the system throughput and the idle probability do not depend on the collision probability when the arrival rate varies but do depend on the collision probability when the traffic intensity varies.

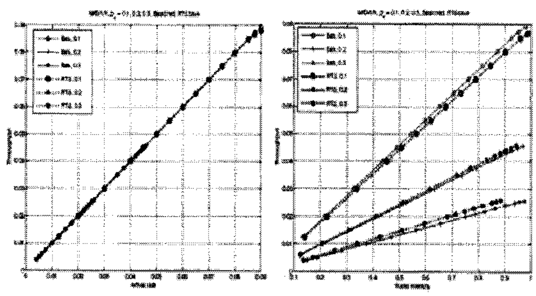

Fig. 8 System throughput w.r.t. λ and ρ

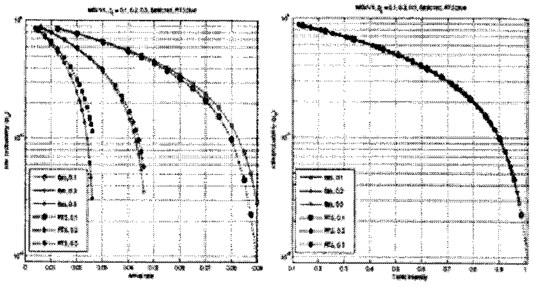

Fig. 9 Idle probability(p_0) w.r.t. λ and ρ

Ⅵ. Conclusion

In this paper, we derived the probability generating function of the MAC layer packet service time when the arrival packet size of each station is a generally distributed random variable. We also presented the comprehensive performance analysis of IEEE 802.11 MAC protocol by investigating the queue dynamics of the M/G/1/K model based on the generally distributed MAC layer packet service time. We compared the performances of two DCF access methods of a wireless station. We take some numerical examples for the system throughput and the queue dynamics including the mean packet delay and packet blocking probability. We need a further study to investigate the queue dynamics with bursty input traffic.

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박 철 근 (Chul-Geun Park) 정회원

1983년2월 부산대학교 수학과 졸업(이학사)

1986년2월 한국과학기술원 응용수학과 졸업(이학석사)

1995년8월 한국과학기술원 수학과 졸업(이학박사)

1986년4월~1997년 2월 한국통신 통신망연구소(선임연구원)

1997년3월~현재 선문대학교 정보통신공학부(교수)

<주관심분야>트래픽공학, 통신망해석, 큐잉이론