Throughput and Packet Delay Analysis of IEEE 802.11 MAC Protocol for Wireless LANs

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ABSTRACT

In this paper, throughput and packet delay performance of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol, which is adopted as a draft standard in IEEE 802.11, is analyzed using a mathematical method based on a renewal theory, and simulation checks are performed, which confirm the goodness of our analysis. In order to analyze of CSMA/CA, we consider that network is composed of finite population and channel is slotted. And, we consider the CSMA/CA protocol as a hybrid protocol of 1-persistent CSMA and p-persistent CSMA protocol. As results of analysis, we have found that the performance of CSMA/CA is degraded as the number of stations, ACK (Acknowledgement) length and DIFS (Distributed coordination function Inter Frame Space) length are increased and theoretical results are very close to simulation ones.

I. INTRODUCTION

Wireless communications and portable communications have been interesting for recent years. More and more stations connect to wireless LANs and demand for various wireless services, which support data, voice and moving pictures, are rapidly increased. The costs for installation and relocation for cable LAN have been increased. However, wireless LANs offers many advantages in installation, maintenance and relocation from the economical and efficient points of view. Wireless LAN manufacturers currently offer a number of nonstandardized products based on conventional radio modem technology, spread spectrum technology in ISM(Industrial, Scientific and Medical) bands, and infrared technology [1]. Since 1990, IEEE Project 802.11 committee has worked to establish a universal standard for wireless LANs protocol for interoperability between competing products. One of important research issue's in wireless LANs is the design and analysis of Medium Access Control(MAC) protocols. In this paper, we consider a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol which is basic mechanism of the IEEE 802.11 MAC protocol, and analyze the performance of CSMA/CA protocols by using a mathematical method based on a renewal theory.

MAC protocols for wireless communications have been widely studied in the literature. There are some analytical studies for CSMA/CA protocols [2],[3], and some simulation studies [4]-[6]. But, Chen assume that CSMA/CA is a non-persistent CSMA and Chhaya calculate the throughput of CSMA/CA with simple model. And, other studies are not presented analytical approaches. In this paper, we present more exactly analytical approach for throughput and normalized packet delay of CSMA/CA protocol.

II. CSMA/CA PROTOCOL

The IEEE 802.11 MAC protocol supports coexisting asynchronous and time-bounded services using different priority levels with different Inter Frame Space (IFS) delay control. Three kinds of the IFS are used to support three backoff priorities such as a Short IFS (SIFS), a Point coordination function IFS (PIFS) and Distributed Coordination function IFS (DIFS) ; SIFS is the shortest IFS and is used for all immediate response action which include acknowledgement (ACK) packet transmission, Clear To Send (CTS) packet transmission and contention-free response packet transmission. PIFS is a middle length IFS and is used for station polling in time-bounded services. And, DIFS is the longest IFS and is used as a minimum delay for asynchronous transmission in the contention period. In this paper, we consider SIFS and DIFS delay to analyze the performance of the CSMA/CA in asynchronous services. A random backoff algorithm of the IEEE 802.11 MAC is similar to that of Ethernet. The backoff delay time is calculated by (1).

$$\text{Backoff Delay} = \text{INT}(CW \times \text{Random}()) \times \text{Slot Time} \quad (1)$$

where CW is a contention window, and CW should increase exponentially after every retransmission attempt. The slot time is the sum of transmitter turn-on time, medium propagation delay and medium busy detect response time. In wireless communication environment, packet transmission suffers from "hidden terminal" IEEE 802.11 MAC protocol provides alternative ways of packet transmission flow control. First, actual data packet only used for packet transmission which is called as Basic CSMA/CA. The other, immediate positive acknow- ledgements are employed to confirm the successful reception of each packet. We call this scheme as Stop-and-Wait(SW) CSMA/CA. We consider two kind of CSMA/CA protocol in the presented paper.

III. System Model

In the CSMA/CA, we assume that the time is slotted with a slot size a (propagation delay/packet transmission time), and all stations are synchronized to start transmission only at slot boundaries. To analyze more exact throughput of the CSMA/CA, we use a finite populations(M stations) and expand it to infinite population model. To use the advantage of the memoryless property [7], we assume that each station has periods, which are independent and geometrically distributed, in which it has no packets. We only consider the case of statistically identical stations. A station generates a new packet with probability g ($0<g<1$) and does not with probability $1-g$. We consider that g includes new arrival and rescheduled packets during a slot. If a station has no packet to transmit, we call this station an empty station and we call the opposite a ready station. We assume that each ready station starts packet transmission with probability p ($0<p\leq1$) and does not with probability $1-p$. The duration of the packet transmission period is assumed to be fixed as a unit of time 1, so the packet transmission time is composed of $1 + (1/a)$ slots. We also assume that the channel is noiseless and all packets are of constant length. We assume that the system has non-capture effect and the propagation delay to be identical for all source-destination pairs.

In this paper, we consider the CSMA/CA is a hybrid protocol of the slotted 1-persistent CSMA and the slotted p-persistent CSMA. We assume that a channel state consists of a sequence of regeneration cycles composed of idle and busy periods. An idle period(denoted by I) is the time in which the channel is idle and no station attempts to access the channel. A busy period(denoted by B) occurs when one or more stations attempt to transmit packets, and ends if no packets have been accumulated at the end of transmission. Let U be the time spent in useful transmission during a regeneration cycle and S be the channel throughput. The throughput S is then given by

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}} \qquad (2)$$

IV. Throughput Analysis

1. Basic CSMA/CA

In the followings, we consider the Basic CSMA/CA protocol, and calculate the expectation of idle period, busy period and useful transmission period. And then, the throughput of CSMA/CA is derived. In CSMA/CA, channel states are illustrated as in Fig. 1. Let us introduce some notation which defines channel states. In Fig. 1, the busy period is divided into several sub-busy periods such that the jth sub-busy period, which is denoted by $B^{(j)}$, is composed of a transmission delay(denoted by $D^{(j)}$) and transmission time(denoted by $T^{(j)}$). In the sub-busy period $B^{(1)}$, $D^{(1)}$ is DIFS delay. However,

$D^{(j)}$ is stochastic random variable, if $j \geq 2$. So, $B^{(j)}$ is composed of a DIFS delay, $D^{(j)}$ and $T^{(j)}$, if $j \geq 2$. The DIFS delay is assumed to have l slots, and the size of DIFS is f ($l \times a$). In the case of Basic CSMA/CA model, transmission period $T^{(j)}$ is fixed at $1 + a$, whether the transmission is successful or not. We call this transmission period as TP. Let J be the number of sub-busy period in a busy period. The busy period is simply given by

$$B = \sum_{j=1}^{J} B^{(j)} \quad , \qquad U = \sum_{j=1}^{J} U^{(j)} \qquad (3)$$

Next, we have to find the number of sub-busy period in a busy period. The busy period continues as long as a packet is generated during the last transmission period. Since J is geometrically distributed, distribution and expectation of J is

$$\text{Prob } [J=j] = [1 - (1-g)^{(TP/a)M}]^{j-1} \cdot (1-g)^{(TP/a)M}$$
$$\overline{J} = \frac{1}{(1-g)^{(TP/a)M}} \quad ; j = 1, 2, \cdots. \qquad (4)$$

The $B^{(1)}$ is occurred when one or more packets arrive in the last slot of the idle period, and $B^{(2)}$ is occurred when one or more packets arrive in $T^{(1)}$. Since $B^{(j)}$ ($j \geq 3$) is independent of $B^{(2)}$ and identically distributed, the expectation of $B^{(j)}$ ($j \geq 2$) is $(\overline{J}-1) \times E[B^{(2)}]$. As the same manner, we get $\{U^{(j)}\}$ easily. Thus, the expectation of busy period and useful transmission time is given by

$$\begin{aligned} \overline{B} &= E[B^{(1)}] + (\overline{J} - 1) E[B^{(2)}] \\ \overline{U} &= E[U^{(1)}] + (\overline{J} - 1) E[U^{(2)}] \end{aligned} \qquad (5)$$

Since the idle period is geometrically distributed, distribution and expectation of the duration for an idle period is given by

$$\text{Prob}[I = ka] = (1-g)^{M(k-1)} \cdot [1 - (1-g)^{M}]$$
$$\overline{I} = \frac{a}{[1-(1-g)^{M}]} \quad ; k = 1, 2, \cdots. \qquad (6)$$

To find $E[D^{(j)}]$ and $E[U^{(j)}]$, let $P_n(X)$ be the probability that n packets arrive in M users during X slots. the $P_n(X)$ is expressed as

$$P_n(X)$$
$$= \text{Prob} \left[\begin{array}{l} n \text{ packets arrive in } M \text{ users during } X \text{ slots} \mid \\ \text{one or more packets arrive in } M \text{ during } X \text{ slots} \end{array} \right]$$
$$= \frac{\binom{M}{n} [1 - (1-g)^X]^n (1-g)^{X(M-n)}}{1 - (1-g)^{XM}} \qquad (7)$$
$$; n = 1, 2, \cdots, M.$$

Furthermore, let $N_0^{(j)}$ be the number of packets accumulated at the end of transmission period, then the distribution of $N_0^{(j)}$ is expressed as

$$\text{Prob}[N_0^{(j)} = n] = P_n(TP/a) \qquad j = 2, 3, \cdots \qquad (8)$$

In order to find the distribution of $D^{(j)}$ when $N_0^{(j)} = n$ and $j \geq 2$, we consider k to be the number of slot boundaries as $k = 0, 1, 2, \cdots$. $D^{(j)}$ is more than k slots in the following cases ; n stations, which are already scheduled to transmit a packet, do not

transmit a packet with probability $(1-p)$ and $(M-n)$ empty stations generate no packet during k slots. Thus, we have

$$\text{Prob}\,[\,D^{(j)} \geq ka\,|\,N_0^{(j)} = n\,] = (1-p)^{kn}\,(1-g)^{\,k(M-n)} \quad (9)$$

From (9), we can derive the expectation of $D^{(j)}$, given $N_0^{(j)} = n$, unconditioning on k and $N_0^{(j)}$ in (9), the expectation of $D^{(j)}$ $(j \geq 2)$ can be calculated.

$$E[\,D^{(j)}\,] =$$
$$\begin{cases} f[1 - (1-g)^M] & ; j=1 \\ \dfrac{a}{1-(1-g)^{(TP/a)M}}\Big(\sum_{k=1}^{\infty}\{(1-p)^k - (1-g)^{(TP/a)} \\ [(1-p)^k - (1-g)^k]\}^M (1-g)^{(TP/a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\Big) \\ & ; j=2, 3, \cdots \end{cases} \quad (10)$$

Using (3), (4)$-$(6), (10), we obtain the sum of expectations of the busy period and the idle period as

$$\overline{B} + \overline{I} =$$
$$f[1 - (1-g)^M] + 1 + a$$
$$+ \frac{1}{(1-g)^{(TP/a)M}}\Big((f+1+a)\,[1 - (1-g)^{(TP/a)M}]$$
$$+ a\sum_{k=1}^{\infty}\{(1-p)^k - (1-g)^{(TP/a)}[(1-p)^k - (1-g)^k]\}^M$$
$$- a(1-g)^{(TP/a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\Big) + \frac{a}{1 - (1-g)^M} \quad (11)$$

Then, we calculate the expected value of useful transmission time $E[U^{(j)}]$. In order to calculate $E[U^{(j)}]$, we consider the condition when $N_0^{(j)} = n$ and $D^{(j)} \geq ka$. Then, we have

$$E\,[\,U^{(j)}\,|\,D^{(j)} \geq ka,\ N_0^{(j)} = n\,]$$
$$= \begin{cases} np(1-p)^{n-1} & ; k=0 \\ [np(1-p)^{n-1}(1-g)^{(M-n)} + \\ (1-p)^n(M-n)g(1-g)^{(M-n)-1}] & ; k>0 \end{cases} \quad (12)$$

Removing k from (3) and using conditional expectation. Since $U^{(1)}$ is the useful transmission time when one or more packets arrive during the last slot of previous idle period, it is equal to $P_1(1)$ in (10). Thus, we have

$$\overline{U} = E[\,U^{(1)}\,] + (\overline{J} - 1)\,E[\,U^{(2)}\,]$$
$$= \frac{Mg(1-g)^{M-1}}{1 - (1-g)^M} + \frac{1}{(1-g)^{(TP/a)M}}$$
$$\cdot \sum_{n=1}^{M}\Big\{\sum_{k=1}^{\infty}[\,np(1-p)^{(k+1)n-1}(1-g)^{(k+1)(M-n)}$$
$$+ (M-n)(1-p)^{(k+1)n}g(1-g)^{(k+1)(M-n)-1}]$$
$$+ np(1-p)^{n-1}\Big\}$$
$$\cdot \Big\{\binom{M}{n}[1 - (1-g)^{(TP/a)}]^n(1-g)^{(TP/a)(M-n)}\Big\} \quad (13)$$

Substituting (11) and (13) into (2), we get the throughput of a slotted CSMA/CA system composed of M identical users, each user has geometric arrival rate g, slot time is a and DIFS delay is f.

Now, we expand our analysis to infinite population model. Let G be the total traffic load by Poisson process and g denote an packet arrival rate during in a slot $(Mg=aG)$. We can modify (11) and (13) for infinite population model as

$$\overline{B} + \overline{I}$$
$$= E[B^{(1)}] + (\overline{J} - 1)E[B^{(2)}] + \overline{I}$$
$$= f[1 - e^{-g}] + 1 + a + \Big(\frac{1}{e^{-TPG}} - 1\Big)$$
$$\cdot \Big[f + \frac{ae^{-g(1+TP)}}{1 - e^{-gTP}}\sum_{n=1}^{\infty}\Big(\frac{[(1-p)gTP]^n}{[1-(1-p)^n e^{-g}]n!}\Big) + 1 + a\Big]$$
$$+ \frac{a}{1 - e^{-g}} \quad (14)$$

$$\overline{U} = E[\,U^{(1)}\,] + (\overline{J} - 1)\,E[\,U^{(2)}\,]$$
$$= \frac{aGe^{-g}}{1 - e^{-g}} + \Big(\frac{1}{e^{-TPG}} - 1\Big)$$
$$\cdot \sum_{n=1}^{M}\Big\{\frac{[np+(1-p)g][e^{-g}(1-p)^n]^2}{(1-p)[1-e^{-g}(1-p)^n]}$$
$$+ np(1-p)^{n-1}\Big\}\Big\{\frac{e^{-TPG}[TP\,G]^n}{[1-e^{-TPG}]n!}\Big\} \quad (15)$$

Using (2), (14) and (15), we can calculate throughput of basic CSMA/CA in infinite population model. We can find the throughput of 1-persistent CSMA, if $p = 1$ and $f = 0$ are substituted in our analysis. Substituting $p = 1$ and $f = 0$ into (14) and (15), and the limit $M \to \infty$, with $aG = gM$ held at a fixed value, we can get the throughput of slotted 1-persistent CSMA for infinite population model, and this result agrees with expressions derived by Klenrock [8].

$$\overline{S} = \frac{Ge^{-G(1+a)}[1 + a - e^{-aG}]}{(1 + a)(1 - e^{-aG}) + a\,e^{-G(1+a)}} \quad (16)$$

2. Stop-and-Wait CSMA/CA

In the following, we consider the SW CSMA/CA protocol and calculate the expectation of idle period, busy period and useful transmission period. The throughput of SW CSMA/CA is derived. In SW CSMA/CA, channel states are illustrated in Fig. 2.

Here the parameters and assumptions are the same as in the case of Basic CSMA/CA except that $T^{(j)}$ successful transmission period(TP_S) is given by $1 + \beta + \gamma + 2a$, when the transmission is successful. When the packet transmission is unsuccessful, ACK packet transmission period is omitted and $T^{(j)}$ (TP_F)is $1+a$. Denoting by TP the duration of the jth transmission period in the busy period, then $(j+1)$th transmission period depends only on TP. This is why the success of $(j+1)$th transmission is determined by the number of arrivals during the jth transmission period. Hence, given that a transmission period(TP), the length of remainder of the busy period is a function of TP, and its average period is denoted by $B(TP)$. Similarly the average useful transmission period in the remainder of the busy period is denoted by $U(TP)$.

$$B(TP) = f + d(TP)$$
$$+ \{(TP_S + [1-(1-g)^{(TP_S/a)}]\,B(TP_S/a)\,\}u(TP)$$
$$+ \{TP_F + [1-(1-g)^{(TP_F/a)}]\,B(TP_F/a)\}\,[1-u(TP)] \quad (17)$$

$$U(TP) = \{1 + [1-(1-g)^{(TP_S/a)}]\,U(TP_S/a)\,\}u(TP)$$
$$+ \{[1-(1-g)^{(TP_F/a)}]\,U(TP_F/a)\}\,[1 - u(TP)] \quad (18)$$

where $d(TP)$ and $u(TP)$ are same as (14) and (18), respectively. If $j \geq 2$, we have to consider that TP is

the both case of TP_S and TP_F. Since a busy period is induced by the first slot before it starts, we get

$$\overline{B} = B(1) ; \qquad \overline{U} = U(1) \qquad (19)$$

Since the duration of successful transmission is different from that of unsuccessful transmission, $B(TP_S)$, $B(TP_F)$, $U(TP_S)$ and $U(TP_F)$ are calculated respectively. Substituting TP by TP_S and TP_F in (17), we can obtain two equations with two unknowns $B(TP_S)$ and $B(TP_F)$ which can be solved easily. The average length of idle period is the same as (9). Thus, we find the throughput of SW CSMA/CA.

$$S = \frac{U(1)}{B(1) + \dfrac{a}{[1 - (1-g)^M]}} \qquad (20)$$

In the infinite population model, we can calculate the throughput of SW CSMA/CA also.

V. DELAY ANALYSIS

1. Basic CSMA/CA

In packet transmission network, the performance is usually represented by channel throughput and packet delay. We denote the expected packet delay L to be the average time from when a packet is generated to when it is successfully received.

In order to calculate the packet delay, we use offered traffic (G) and throughput (S). And, we use the average number of retransmission for a packet which is $(G/S - 1)$. We now introduce the average delay R for a packet from sensing channel to accessing channel. This is one of the three following cases 1) A packet arrives and senses the channel as idle period. 2) A packet arrives and senses the channel as delay period(D). 3) A packet arrives and sense the channel as transmission period. In the case of 1), an arbitrary packet is arrived and will find the channel idle with probability $\overline{I}/(\overline{B}+\overline{I})$. And, its average delay is DIFS. In case 2), a packet is arrived and will find the channel in the delay period with probability $\overline{D}/(\overline{B}+\overline{I})$. In this case its average delay is also DIFS. In last case, a packet is arrived and will find the channel in the period of other packet transmission period with probability $(\overline{B}-\overline{D})/(\overline{B}+\overline{I})$ In this case the packet waits for channel to be idle and delays by backoff algorithm. Its average delay can be calculated by residual life period in renewal theory. So, we can get average delay R as

$$\overline{R} = \frac{\overline{I}}{\overline{B}+\overline{I}} f + \frac{\overline{D}}{\overline{B}+\overline{I}} f$$
$$+ \frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}} \left[\frac{\overline{TP^2}}{2\,\overline{TP}} + E[D] \right] \qquad (21)$$

In (21), we can obtain $E[D]$ using (10) and calculate $\overline{D}$ by

$$\overline{D} = E[D^{(1)}] + (\overline{J} - 1)E[D^{(2)}] \qquad (22)$$

We can obtain normalized average packet delay by

$$L = \left(\frac{G}{S} - 1 \right) [\, TP + \overline{Y} + \overline{R} \,] + TP + \overline{R} \qquad (23)$$

where, Y denotes random delay for a packet that senses the busy channel and then waits for Y before sensing the channel. TP_B is the packet transmission period with $(1+a)$. In infinite population model, we can obtain the packet delay easily.

2. Stop-and-Wait CSMA/CA

Similar to the case of Basic CSMA/CA, we calculate the average delay for the interval of successive transmission $(\overline{R})$ by

$$\overline{R} = \frac{\overline{I}}{\overline{B}+\overline{I}} f + \frac{\overline{D}}{\overline{B}+\overline{I}} f \qquad (24)$$
$$+ \frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}} \left\{ P_{Succ} \left[\frac{\overline{TP_S^2}}{2\,\overline{TP_S}} + d(TP_S/a) \right] \right.$$
$$\left. + P_{Fail} \left[\frac{\overline{TP_F^2}}{2\,\overline{TP_F}} + d(TP_F/a) \right] \right\}$$

where, TP_S is $1+\beta+\gamma+2a$ and TP_F is $\gamma+a$. P_{Succ} denotes the probability of a successful packet transmission which is (G/S) and P_{Fail} is $1-P_{Succ}$. Other notation is same to that of previous Section, but $\overline{D}$ have to be calculated differently. $\overline{D}$ is as follows

$$\overline{D} = $$
$$f+\{d(TP_S/a)+[1-(1-g)^{(TP_S/a)}]\,D(TP_S/a)\}$$
$$\cdot u(1)+\{d(TP_F/a)+[1-(1-g)^{(TP_F/a)}] \qquad (25)$$
$$\cdot D(TP_F/a)\}\,[1-u(1)]$$

where $d(TP_S/a)$ and $d(TP_F/a)$ can be obtained, substituting TP by TP_S and TP_F in (10). $D(TP_S/a)$ and $D(TP_F/a)$ can be calculated by substituting 1 by TP_S and TP_F respectively. Since the backoff delay is determined by previous transmission period, we have to calculate the backoff delay in both cases of successful and unsuccessful transmission period. Then, normalized delay L is obtained easily by substituting former TP by TP_F and later TP by TP_S in (23).

VI. NUMERICAL RESULTS

Based on the analysis presented in the previous sections, some numerical results are shown in this section. To check the validity of our analysis, we have performed computer simulations under real communication environments. We have considered the performance with the variation of M(the number of users), g (offered load) and δ(ACK transmission period). We have considered values of each parameters based on real communication environments and the IEEE 802.11 standard draft as well [9].

The throughput and packet delay for Basic CSMA/CA system versus offered traffic load G is plotted in Fig. 3. In Fig. 3, a solid line represents

analytical results and a triangle represents simulation check point. We have found that the delay raise rapidly when the offered load is increased above the value 10. Simulation results are close to analytical ones. Fig. 4 and 5 show the throughput and delay curve versus offered traffic load for the Basic CSMA/CA system with varying the number of users, The throughput is not very sensitive to the number of users when the traffic is low, while it is degraded when the traffic is increased above 10. Fig. 6 and 7 present the throughput and packet delay of SW CSMA/CA for the variation of the length of the ACK packet transmission period(δ). The throughput is degraded linearly as increasing the value of δ, when the load is above 1. And, the normalized delay is raised rapidly when the traffic is increased, and linearly when the value of δ is increasing. Fig. 8 and 9 show the performance of SW CSMA/CA for varying transmission probability p. We could found that the performance is maximized when the p is from 0.03 to 0.04 for the traffic load in the range from 0.1 to 4.

VII. Conclusions

In this paper, we have analyzed the performance of CSMA/CA protocols in wireless LANs and verified our analysis by computer simulations. The throughput and packet delay of the CSMA/CA protocol, adopted as the IEEE 802.11 MAC protocol, for which an exact analysis has not been presented currently, has been analyzed and presented in this paper. We have considered that network is composed of finite number of users and then this was expanded with an infinite population model. As results, we have found that analysis results are very close to simulated ones and the results of the expanded infinite population model for slotted 1-persistent CSMA is agreed upon with previous works. Based on the analysis, the throughput of the slotted CSMA/CA is affected by traffic loads, DIFS, and ACK packet length as intuitively expected. So, we have found that the length of DIFS should be considered carefully in wireless LANs.

We have developed a technique for the analysis of CSMA/CA protocols. The analysis techniques and results of this paper will be helpful to the practical interest in wireless LANs.

References

[1] K.Pahlavan and A. H. Levesque, "Wireless Data Communications," *Proceeding of the IEEE* , vol. 82, no. 9, pp.1398 − 1430, Sep. 1994

[2] K. C. Huang and K. C. Chen, "Interference Analysis of Nonpersistent CSMA with Hidden Terminals in Multicell Wireless Data Networks," *Proc. IEEE PIMRC '95*, pp. 907-911, Toronto, Canada Sep. 27-29, 1995.

[3] H. S. Chhaya and S. Gupta, "Throughput and Fairness Properties of Asynchronous Data Transfer Methods in the IEEE 802.11 MAC Protocol," *Proc. IEEE PIMRC '95*, pp. 613-617, Toronto, Canada Sep. 27-29, 1995.

[4] M. Nor and J. Semarak, "Performance of CSMA-CA MAC Protocol for Distributed Radio Local Area Networks," *Proc. IEEE PIMRC '95*, pp. 912-916, Toronto, Canada Sep. 27-29, 1999.

[5] A. Visser and M. E. Zarki, "Voice and data transmission over an 802.11 Wireless network," *Proc. IEEE PIMRC '95*, pp. 648-652, Toronto, Canada Sep. 27-29, 1995.

[6] Weinmiller, H. Woesner, J. P. Ebert and A. Wolisz, "Analyzing the RTS/CST Mechanism in the DFWMAC Media Access Protocol for Wireless LAN," *Proc. IFIP TC6 Workshop Personal Wireless Comm.* Apr. 1995 ; http://ftsu10.ee.tu-derlin.de/bibl/ ours/

[7] H. Takagi, L. Kleinrock, " Throughput Analysis for CSMA Systems", *IEEE Trans. Commun.*, vol. COM − 33, no. 7, pp. 627-638, Jul. 1985.

[8] L. Kleinrock and F. A. Tobagi, "Packet Switching in Radio Channels: Part I − Carrier Sense Multiple − Access Modes and Their Throughput − Delay Characteristics" *IEEE Trans. on Commun.*, vol. com-23, no. 12, pp. 1400-1416, Dec. 1975.

[9] "Wireless LAN Medium Access Control (MAC) And Physical Layer(PHY) Specification," IEEE Standard Draft, Dec. 1994.
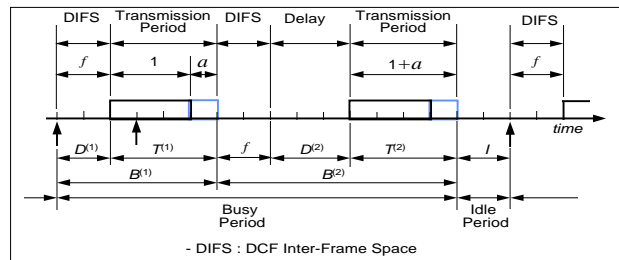
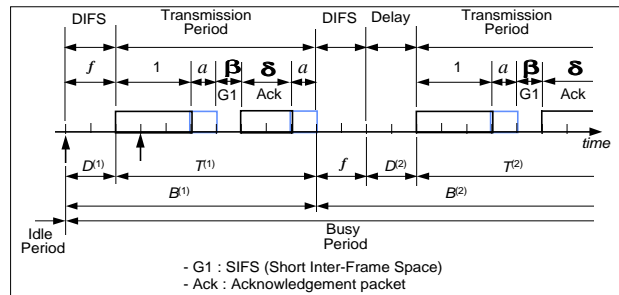Fig. 1 Channel state in slotted channel CSMA/CA

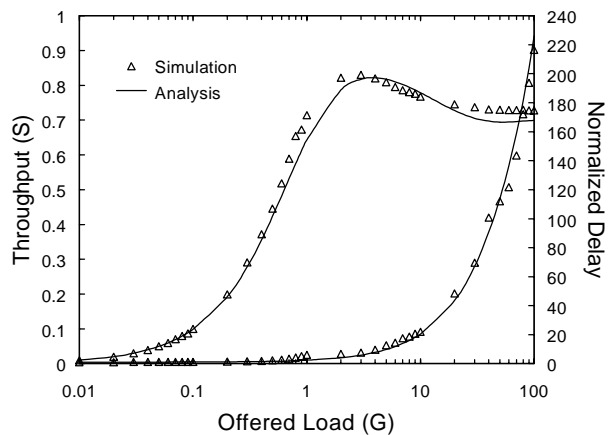Fig. 2 Channel model in the slotted Stop-and-Wait CSMA/CA

Fig. 3 Throughput and packet delay of CSMA/CA protocol when the number of users is fixed at 20 ($a = 0.01$, $p = 0.03$, $f = 0.03$, $Y = 0.06$)
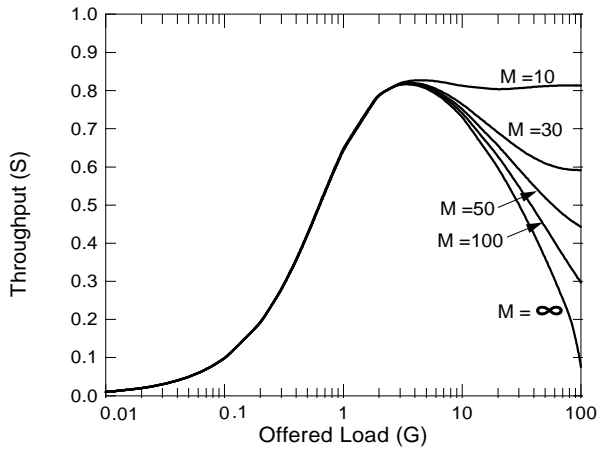
Fig. 4 Throughput of Basic CSMA/CA protocol for varying the number of users
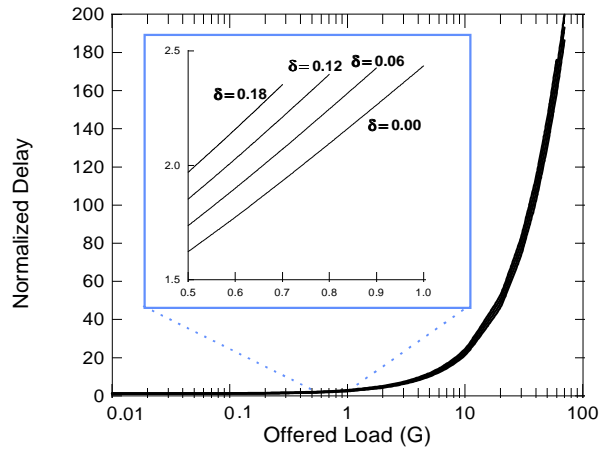($a = 0.01$, $p = 0.03$, $f = 0.03$, $Y = 0.06$)

Fig. 7 Packet delay of Stop-and-Wait ARQ CSMA/CA protocol for varying the length of ACK
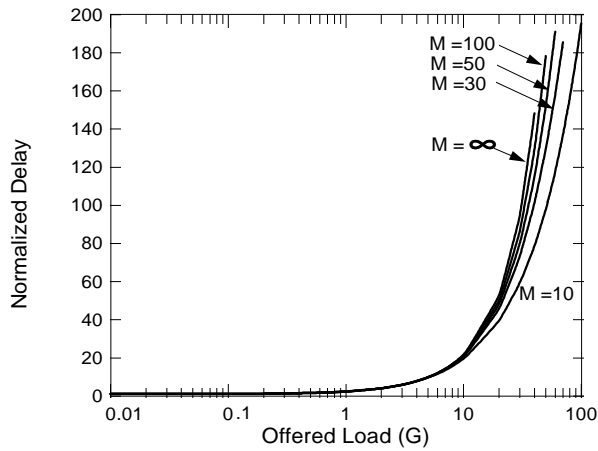(a=0.01, p=0.03, M=30, f=0.03, β=0.01, Y=0.06)

Fig. 5 Packet delay of Basic CSMA/CA protocol for varying the number of users
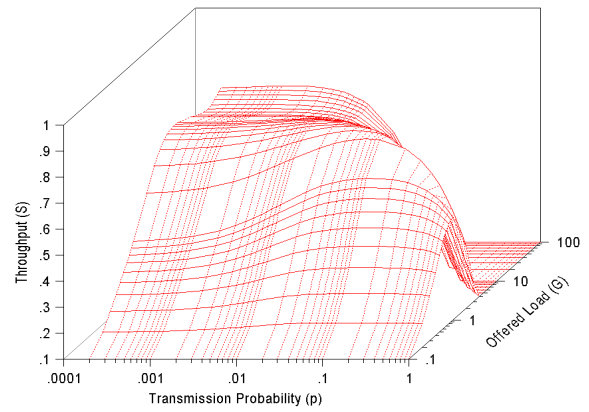($a = 0.01$, $p = 0.03$, $f = 0.03$, Y $= 0.06$)

Fig. 8 Throughput of Stop-and-Wait ARQ CSMA/CA for varying the p
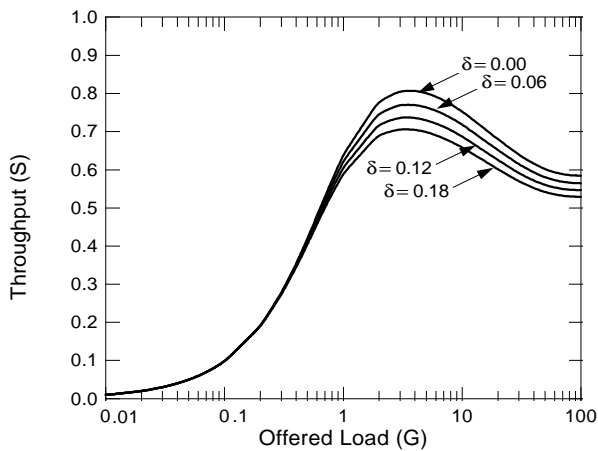($a = 0.01$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$)

Fig. 6 Throughput of Stop-and-Wait ARQ CSMA/CA for varying the length of ACK
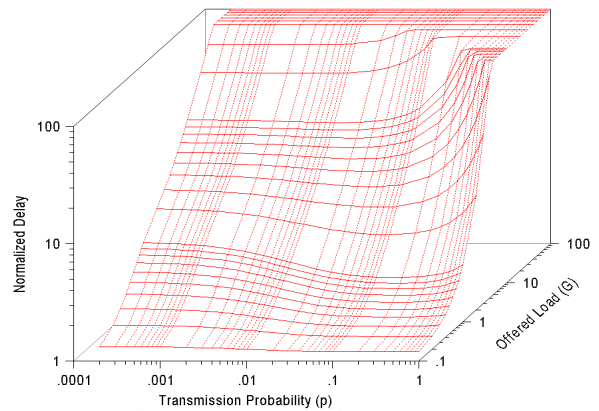(a=0.01, p=0.03, M=30, f=0.03, β=0.01)

Fig. 9 Packet delay of Stop-and-Wait ARQ CSMA/CA for varying the p
($a = 0.01$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$)