Wireless Personal Communications **11:** 161–183, 1999.

Performance of Carrier Sense Multiple Access with Collision Avoidance Protocols in Wireless LANs

JAE HYUN KIM and JONG KYU LEE
Data Communication Laboratory, Department of Computer Science and Engineering, Hanyang University, Sa 1 dong 1271, Ansan, Korea
E-mail: {jhkim and jklee} @commlab.hanyang.ac.kr

Abstract. The performance of Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocols, which is adopted as a draft standard in IEEE 802.11, is analyzed in the view of throughput and packet delay. We consider three kinds of CSMA/CA protocols, which include Basic, Stop-and-Wait and 4-Way Handshake CSMA/CA, and introduce a theoretical analysis for them. First, we consider that a network consists of a finite population and then expand to an infinite population model. We model the CSMA/CA protocol as a hybrid protocol of a 1-persistent CSMA and a p-persistent CSMA protocol. We calculate the throughput and packet delay for three kinds of CSMA/CA protocols and verify analytical results by computer simulation. We have found that 4-Way Handshake CSMA/CA shows better performance than those of other two type CSMA/CA in high traffic load and analytical results are very close to simulation ones.

Keywords: wireless LAN, MAC protocol, CSMA/CA, throughput, packet delay, random access.

1. Introduction

In recent years there has been great interest in wireless and portable communications. More and more terminals connect to wireless Local Area Networks (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 points of view of cost and efficiency. 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 [2] and ETSI (European Telecommunications Standards Institute) set up an ad hoc group to investigate radio LANs in 1991 [3]. One of the important research issues in wireless LANs is the design and analysis of Medium Access Control (MAC) protocols. In this paper, we consider a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol which is a 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. There are some analytical studies for CSMA/CA protocols and some simulation studies [4–8]. But, Chen assume that CSMA/CA is a non-persistent CSMA [4] and Chhaya calculate the throughput of CSMA/CA with a simple model [5]. However, the characteristics of CSMA/CA cannot described by non-persistent CSMA model. Other studies do not present analytical approaches [6–8]. Therefore, we present an exactly analytical approach for throughput and normalized packet delay of CSMA/CA protocols and compare the performance of three types of CSMA/CA protocols in wireless LANs in this paper. We also check the analytical results with computer simulations. The remainder of this paper is organized as follows. In Section 2, the properties of CSMA/CA protocols in IEEE 802.11 is described and in Section 3, the system model is presented. Throughput of three kinds of CSMA/CA is analyzed in Section 4, and in Section 5, packet delay is calculated. In Section 6, some numerical results and simulation results are reported. Finally, we give concluding remarks in Section 7.

2. CSMA/CA Protocol

Since different physical transmission layers are supported by IEEE 802.11, the wireless MAC protocol should be transparency to physical layers, which include Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS) and diffused infrared. Since spectrum is a scare resource above all different physical layers, the throughput and packet delay performance is one of the most critical considerations in the design of a wireless MAC protocol.

The basic protocol level in the 802.11 MAC protocol is the Distributed Coordination Function (DCF), which supports asynchronous communication between multiple users [9]. The DCF allows to share medium between similar and dissimilar systems through the use of the CSMA/CA and a random backoff delay algorithm. The CSMA/CA is similar to the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) used in a Ethernet. As the Ethernet, the CSMA/CA uses carrier-sense mechanism to determine whether other terminals are using the medium. If a channel is sensed idle, the packet transmission is started immediately in both cases. However, if the channel is sensed busy, the CSMA/CA and the CSMA/CD operate differently to resolve the contention. In the case of the CSMA/CD, when a terminal senses a busy channel, it waits until the channel goes idle and then it transmits a packet with probability one. When two or more terminals are waiting to transmit, a collision is absolutely occurred because each terminal will transmit immediately at the end of channel busy period. While a terminal, operates in the CSMA/CA protocol, senses the busy channel, it waits until the channel goes idle and waits for delay period, which is called backoff delay. In the CSMA/CA, the collision probability between multiple terminals under above situation is reduced since a random backoff arrangement is used to resolve medium contention conflicts. The Collision Detection (CD) function detects collisions in the CSMA/CD, but the CD function is not viable in wireless LANs because the dynamic range of signals in the medium is very large. Thus, packet transmission errors are increased in wireless communication environments.

The IEEE 802.11 MAC protocol supports coexisting asynchronous and time-bounded services using different priority levels with different Inter Frame Space (IFS) delay controls. Three kinds of 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 actions which include acknowledgement (ACK) packet transmissions, Clear To Send (CTS) packet transmissions and contention-free response packet transmissions. PIFS is a middle length IFS and is used for terminal polling in time-bounded services. 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. We consider that transmitters in the CSMA/CA protocol are operated as following manners.

- If medium is idle longer than DIFS, then transmit a data packet immediately.
- If medium is busy, defer until the medium goes idle and DIFS is detected, and go into backoff.

A random backoff algorithm of the IEEE 802.11 MAC is similar to that of Ethernet. The backoff delay time is calculated by (1)

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

where INT($*$) means the function which returns the integer value of the $*$, Random() is the function which generates the pseudo random number between 0 and 1, and the 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 environments, packet transmission suffers from "hidden terminal", so IEEE 802.11 MAC protocol provides three alternative ways of packet transmission flow control [9]. First, actual data packet is only used for packet transmission which is called Basic CSMA/CA. Second, immediate positive acknowledgements are employed to confirm the successful reception of each packet. We call this scheme Stop-and-Wait (SW) CSMA/CA. The last is 4-Way Handshake (4-WH) CSMA/CA which use Request To Send (RTS) and Clear To Send (CTS) packets prior to the transmission of the actual data packet. The packet transmission flow of three kinds of CSMA/CA is summarized as follow

1. Basic CSMA/CA : Data - Data - $\cdots$
2. SW CSMA/CA : Data - ACK - Data - ACK -$\cdots$
3. 4WH CSMA/CA : RTS - CTS - Data - ACK -$\cdots$

We analyze the channel throughput and normalized packet delay of three kinds of CSMA/CA protocols in the paper.

3. 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 terminals are synchronized to start transmission only at slot boundaries. To analyze exact throughput of the CSMA/CA, we use a finite population (M terminals) and expand it to an infinite population model. To use the advantage of the memoryless property [10], we assume that each terminal has periods, which are independent and geometrically or exponentially distributed, in which there are no packets. We only consider the case of statistically identical terminals. A terminal 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 terminal has no packet to transmit, we call this terminal an empty terminal and we call the opposite a ready terminal. We assume that each ready terminal starts packet transmission with probability p ($0 < p \leq 1$) and this p is related to CW in the backoff equation (1). 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 as a hybrid protocol of the

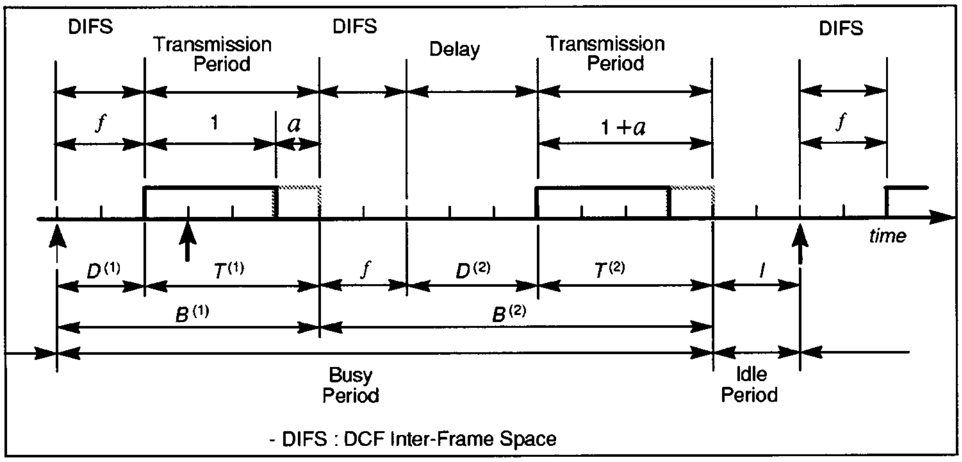

Figure 1. Channel model in the Basic CSMA/CA.

slotted 1-persistent CSMA and 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 terminal attempts to access the channel. A busy period (denoted by B) occurs when one or more terminals attempt to transmit packets, and ends if no packets have been accumulated at the end of the 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

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}} . \tag{2}$$

4. Throughput Analysis

4.1. 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. The throughput of Basic CSMA/CA is then derived. In Basic CSMA/CA, channel states are illustrated as in Figure 1. Let us introduce some notations which define channel states. Here 1 is the data packet transmission period and a means the propagation delay. The DIFS delay is assumed to have l slots, and the size of DIFS is $f (= l \times a)$. In Figure 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 the stochastic random variable, if $j \geq 2$. $B^{(j)}$ is composed of a DIFS delay, $D^{(j)}$ and $T^{(j)}$. In the case of the Basic CSMA/CA model, transmission period $T^{(j)}$ is fixed at $1 + a$, whether the transmission is successful or not. Let J be the number of sub-busy periods in a busy period. The busy period B and the useful transmission period U are simply given by

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

where $B^{(j)}$ means the sub-busy period and the $U^{(j)}$ denotes the sub-useful transmission period. Next, we have to find the number of sub-busy periods in a busy period. In CSMA/CA every terminal transmits a pending packet after it detects the free medium for greater than or equal to a DIFS. Therefore, the busy period continues in the case that a packet is generated during the last transmission period as well as the last DIFS delay. Let TP be the sum of the last transmission period and the last DIFS delay, then TP is $1 + a + f$ in the Basic CSMA/CA model. Since J is geometrically distributed, the distribution and the expectation of J are

$$\begin{aligned}\Pr[J = j] &= \left[1 - (1-g)^{(TP/a)M}\right]^{j-1}(1-g)^{(TP/a)M},\\ \overline{J} &= \frac{1}{(1-g)^{(TP/a)M}} \;;\quad j = 1, 2, \cdots.\end{aligned} \tag{4}$$

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

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

The duration of the idle period is geometrically distributed by

$$\Pr[I = ka] = (1-g)^{M(k-1)} \cdot [1 - (1-g)^M]; \quad k = 1, 2, \cdots. \tag{6}$$

Since the idle period is geometrically distributed, the expectation is given by

$$\overline{I} = \frac{a}{[1 - (1-g)^M]}. \tag{7}$$

To find $E[D^{(j)}]$ and $E[U^{(j)}]$, let $P_n(X)$ be the probability that n of M users generate a packet during X slots, given that $n \geq 1$. The $P_n(X)$ is expressed as

$$P_n(X) = \frac{\binom{M}{n}\left[1 - (1-g)^X\right]^n (1-g)^{X(M-n)}}{1 - (1-g)^{XM}} \quad ; n = 1, 2, \cdots, M. \tag{8}$$

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

$$\Pr[N_0^{(j)} = n] = P_n(TP/a) \quad j = 2, 3, \cdots. \tag{9}$$

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 greater than equal to k slots in the following cases; n terminals, which are already scheduled to transmit a packet, do not transmit a packet with probability $(1 - p)$ and $(M - n)$ empty terminals generate no packet with probability $(1 - g)$ during k slots. Thus, we have

$$\Pr[D^{(j)} \geq ka | N_0^{(j)} = n] = (1-p)^{kn}(1-g)^{k(M-n)}. \tag{10}$$

Unconditioning $N_0^{(j)}$ in (10), we can derive the expectation of $D^{(j)}$, given $N_0^{(j)} = n$.

$$E[D^{(j)}] = \begin{cases} f[1-(1-g)^M] & ; j = 1 \\ \frac{a}{1-(1-g)^{(TP/a)M}} \left(\sum_{k=1}^{\infty} \left\{(1-p)^k - (1-g)^{(TP/a)} \right.\right. & \\ \left.[(1-p)^k - (1-g)^k]\right\}^M (1-g)^{(TP/a)M} & \\ \left.\sum_{k=1}^{\infty}(1-g)^{kM}\right) & ; j = 2, 3, \cdots \end{cases} \tag{11}$$

Using (3), (4), (7), (11), we obtain the sum of expectations of the busy period and the idle period as

$$\begin{aligned} \overline{B} + \overline{I} &= E[B^{(1)}] + (\overline{J} - 1)E[B^{(2)}] + \overline{I} \\ &= E[D^{(1)}] + 1 + a + \left[\frac{1}{(1-g)^{(TP/a)M}} - 1\right]\left(f + E[D^{(2)}] + 1 + a\right) + \overline{I} \\ &= f[1-(1-g)^M] + 1 + a + \frac{1}{(1-g)^{(TP/a)M}} \\ &\quad \cdot \left((f+1+a)[1-(1-g)^{(TP/a)M}] + a\sum_{k=1}^{\infty}\left\{(1-p)^k - (1-g)^{(TP/a)}\right.\right. \\ &\quad \left.\left. \cdot [(1-p)^k - (1-g)^k]\right\}^M - a(1-g)^{(TP/a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\right) + \frac{a}{1-(1-g)^M}. \end{aligned} \tag{12}$$

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

$$E[U^{(j)}|D^{(j)} \geq ka, N_0^{(j)} = n] = \begin{cases} np\,(1-p)^{n-1} & ; k = 0 \\ np\,(1-p)^{n-1}\,(1-g)^{M-n} & \\ +(1-p)^n\,(M-n)g\,(1-g)^{(M-n)-1} & ; k > 0 \end{cases} \tag{13}$$

Using conditional expectation, we can obtain the mean successful transmission period. Since $U^{(1)}$ is the useful transmission time when one or more packets arrive during the last slot of the previous idle period, it is equal to $P_1(1)$ in (8). Thus, we have

$$\begin{aligned} \overline{U} &= E[U^{(1)}] + (\overline{J} - 1)E[U^{(2)}] \\ &= \frac{Mg(1-g)^{M-1}}{1-(1-g)^M} + \frac{1}{(1-g)^{(TP/a)M}}\sum_{n=1}^{M}\left\{\sum_{k=1}^{\infty}\left[np(1-p)^{(k+1)n-1}(1-g)^{(k+1)(M-n)}\right.\right. \\ &\quad \left.\left. +(M-n)(1-p)^{(k+1)n}g(1-g)^{(k+1)(M-n)-1}\right] + np(1-p)^{(n-1)}\right\} \\ &\quad \cdot \left\{\binom{M}{n}[1-(1-g)^{(TP/a)}]^n(1-g)^{(TP/a)(M-n)}\right\}. \end{aligned} \tag{14}$$

Substituting (12) and (14) into (2), we get the throughput of a slotted Basic 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 the infinite population model. Let G be the total traffic load by the Poisson process and g denotes a packet arrival rate during a slot ($Mg = aG$). The derivations of the throughput in the infinite population model are shown in Appendix A.1. We can also 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 (12) and (14), and the

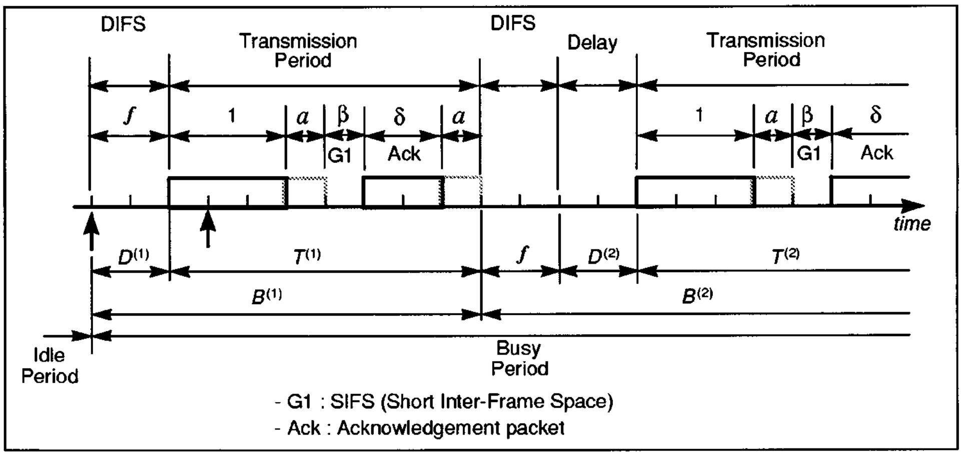

Figure 2. Channel model in the Stop-and-Wait CSMA/CA.

limit $M \to \infty$, with $aG = gM$ held at a fixed value, we can get the throughput of slotted 1-persistent CSMA for the infinite population model, and this result agrees with expressions derived by Kleinrock [11].

$$\overline{S} = \frac{Ge^{-G(1+a)}[1 + a - e^{-aG}]}{(1 + a)(1 - e^{-aG}) + ae^{-G(1+a)}}. \tag{15}$$

4.2. Stop-and-Wait CSMA/CA

In the following, we consider the SW CSMA/CA protocol and calculate the channel throughput. For SW CSMA/CA, channel states are illustrated in Figure 2. To calculate the throughput of SW CSMA/CA, we define the new notation. Let β be the length of Short Inter-Frame Space(SIFS) and δ be the length of ACK packet transmission period. Here the parameters and assumptions are the same as in the case of Basic CSMA/CA except that successful transmission period (TP_S) is given by $1+\beta+\delta+2a+f$, when the transmission is successful. Note that TP_S includes the DIFS delay since terminals, generate a packet in the period of the last DIFS delay, have to wait for the channel goes idle. When the packet transmission is unsuccessful, the ACK packet transmission period is omitted and the unsuccessful transmission period (TP_F) is $1 + a + f$.

Notice that here a success or failure of a transmission period in the busy period depends on the length of the preceding transmission period, except for the first transmission period $(T^{(1)})$ that depends on the preceding last slot in the idle period. Denoting by Z the duration of the jth transmission period in the busy period, then $(j + 1)$th transmission period depends only on Z. This is why the success of $(j + 1)$th transmission is determined by the number of packet arrivals during the jth transmission period. Hence, given a transmission period (Z), the length of the remainder of the busy period is a recursive function of Z, and its average period is denoted by $B(Z)$. Similarly the average useful transmission period in the remainder of the busy period is denoted by $U(Z)$. See [10] and [12] for a more detail calculation technique.

$$\begin{aligned} B(Z) &= d(Z) + \left\{TP_S + \left[1 - (1 - g)^{(TP_S/a)}\right] B\left(TP_S\right)\right\} u(Z) \\ &\quad + \left\{TP_F + \left[1 - (1 - g)^{(TP_F/a)}\right] B\left(TP_F\right)\right\} [1 - u(Z)], \end{aligned} \tag{16}$$

$$U(Z) = \left\{1 + [1-(1-g)^{(TP_S/a)}]U(TP_S)\right\}u(Z) + \left\{[1-(1-g)^{(TP_F/a)}]U(TP_F)\right\}[1-u(Z)], \tag{17}$$

If $j \geq 2$, we have to consider that Z is the case of both TP_S and TP_F. 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 Z by TP_S and TP_F in (16), we can obtain two equations with two unknowns $B(TP_S)$ and $B(TP_F)$ which is easily obtained and so does the case of $U(TP_S)$ and $U(TP_F)$.

$$B(TP_S) = \frac{\begin{bmatrix} [1-(1-g)^{(TP_F/a)M}][TP_S + f + d(TP_S)]u(TP_F) \\ -\left\{[1-(1-g)^{(TP_F/a)M}][TP_S + f + d(TP_F)] - \alpha - \beta - \gamma\right\}u(TP_S) \\ +[1-(1-g)^{(TP_F/a)M}][d(TP_F) - d(TP_S)] + d(TP_S) + f + 1 + a \end{bmatrix}}{\begin{bmatrix} (1-g)^{(TP_F/a)M}\left\{1-[1-(1-g)^{(TP_S/a)M}]u(TP_S)\right\} \\ +(1-g)^{(TP_S/a)M}\left\{[1-(1-g)^{(TP_F/a)M}]u(TP_F)\right\} \end{bmatrix}},$$

$$B(TP_F) = \frac{\begin{bmatrix} (1+a+f)\left\{[1-(1-g)^{(TP_S/a)M}][u(TP_F) - u(TP_S)] + 1\right\} \\ -[1-(1-g)^{(TP_S/a)M}][u(TP_S)d(TP_F) - u(TP_F)d(TP_S)] \\ +d(TP_F) + u(TP_F)(a + \beta + \gamma) \end{bmatrix}}{\begin{bmatrix} (1-g)^{(TP_F/a)M}\left\{1-[1-(1-g)^{(TP_S/a)M}]u(TP_S)\right\} \\ +(1-g)^{(TP_S/a)M}\left\{[1-(1-g)^{(TP_F/a)M}]u(TP_F)\right\} \end{bmatrix}}, \tag{18}$$

and

$$U(TP_S) = \frac{u(TP_S) - [1-(1-g)^{(TP_F/a)M}][u(TP_S) - u(TP_F)]}{\begin{bmatrix} (1-g)^{(TP_F/a)M}\left\{1-[1-(1-g)^{(TP_S/a)M}]u(TP_S)\right\} \\ +(1-g)^{(TP_S/a)M}\left\{[1-(1-g)^{(TP_F/a)M}]u(TP_F)\right\} \end{bmatrix}},$$

$$U(TP_F) = \frac{u(TP_F)}{\begin{bmatrix} (1-g)^{(TP_F/a)M}\left\{1-[1-(1-g)^{(TP_S/a)M}]u(TP_S)\right\} \\ +(1-g)^{(TP_S/a)M}\left\{[1-(1-g)^{(TP_F/a)M}]u(TP_F)\right\} \end{bmatrix}}, \tag{19}$$

where $d(*)$ and $u(*)$ terms are derived from (11) and (14), respectively.

$$d(1) = f[1-(1-g)^M],$$

$$d(TP_S) = \frac{a}{1-(1-g)^{(TP_S/a)M}}\left(\sum_{k=1}^{\infty}\left\{(1-p)^k - (1-g)^{(TP_S/a)}\left[(1-p)^k - (1-g)^k\right]\right\}^M \cdot (1-g)^{(TP_S/a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\right),$$

$$d(TP_F) = \frac{a}{1-(1-g)^{(TP_F/a)M}}\left(\sum_{k=1}^{\infty}\left\{(1-p)^k - (1-g)^{(TP_F/a)}\left[(1-p)^k - (1-g)^k\right]\right\}^M \cdot (1-g)^{(TP_F/a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\right), \tag{20}$$

$$
\begin{aligned}
u(1) &= \frac{Mg(1-g)^{M-1}}{1-(1-g)^M}, \\
u(TP_S) &= \frac{1}{(1-g)^{(TP_S/a)M}} \sum_{n=1}^{M} \left\{ \sum_{k=1}^{\infty} \left[np(1-p)^{(k+1)n-1}(1-g)^{(k+1)(M-n)} \right.\right. \\
&\quad \left.\left. +(M-n)(1-p)^{(k+1)n} g(1-g)^{(k+1)(M-n)-1} \right] + np(1-p)^{(n-1)} \right\} \\
&\quad \cdot \left\{ \binom{M}{n} [1-(1-g)^{(TP_S/a)}]^n (1-g)^{(TP_S/a)(M-n)} \right\}, \\
u(TP_F) &= \frac{1}{(1-g)^{(TP_F/a)M}} \sum_{n=1}^{M} \left\{ \sum_{k=1}^{\infty} \left[np(1-p)^{(k+1)n-1}(1-g)^{(k+1)(M-n)} \right.\right. \\
&\quad \left.\left. +(M-n)(1-p)^{(k+1)n} g(1-g)^{(k+1)(M-n)-1} \right] + np(1-p)^{(n-1)} \right\} \\
&\quad \cdot \left\{ \binom{M}{n} [1-(1-g)^{(TP_F/a)}]^n (1-g)^{(TP_F/a)(M-n)} \right\}. \qquad (21)
\end{aligned}
$$

Since a busy period is induced by the first slot before it starts [12], we get

$$
\begin{aligned}
\overline{B} &= B(1) \\
&= d(1) + \left\{ TP_S + \left[1-(1-g)^{(TP_S/a)}\right] B(TP_S) \right\} u(1) \\
&\quad + \left\{ TP_F + \left[1-(1-g)^{(TP_F/a)}\right] B(TP_F) \right\} [1-u(1)], \qquad (22)
\end{aligned}
$$

$$
\begin{aligned}
\overline{U} &= U(1) \\
&= \left\{ 1 + [1-(1-g)^{(TP_S/a)}] U(TP_S) \right\} u(1) \\
&\quad + \left\{ [1-(1-g)^{(TP_F/a)}] U(TP_F) \right\} [1-u(1)], \qquad (23)
\end{aligned}
$$

where $d(1)$ and $u(1)$ are obtained from (20) and (21). The average length of idle period is the same as in (7). Thus, we find the throughput of SW CSMA/CA using (7), (22) and (23).

$$
S = \frac{U(1)}{B(1) + \frac{a}{[1-(1-g)^M]}}. \qquad (24)
$$

In the infinite population model, we can calculate the throughput of SW CSMA/CA in a similar manner as in the case of Basic CSMA/CA. The rigorous derivations are given in Appendix A.2.

4.3. 4-Way Handshake CSMA/CA

We now proceed to calculate the throughput of 4-Way Handshake CSMA/CA. Since packet transmission is not absolutely reliable in wireless communication environments, IEEE 802.11 provides 4-Way handshaking with a CSMA/CA mechanism. The carrier sense mechanism is achieved by distributing medium busy reservation information through an exchange of special

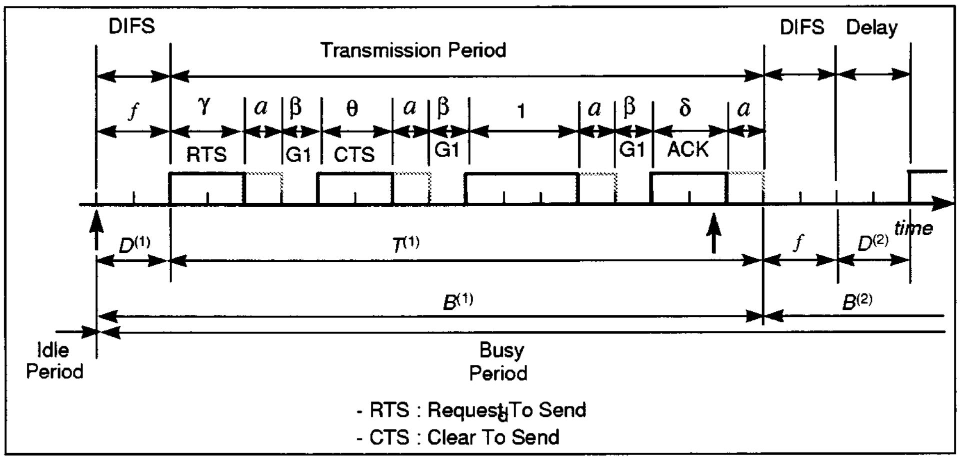

Figure 3. Channel model in the 4-Way Handshake CSMA/CA.

small RTS and CTS frame prior to the actual data frame. If a collision occurs during the RTS packet transmission period, the packet transmission is terminated immediately and a new packet transmission is started.

We assume that normalized packet transmission of RTS and CTS are γ and θ respectively. The channel model for slotted 4-WH CSMA/CA is shown in Figure 3. If the RTS packet transmission is successful, transmission period ($T^{(j)}$) is composed of RTS packet transmission period (γ), CTS packet transmission period (θ), data packet transmission period (1), ACK packet transmission period (δ), 3 SIFS (3β) and 4 propagation delay ($4a$). We denote that TP_{4S} is the sum of the successful transmission period and DIFS delay. Therefore, TP_{4S} is $1 + \gamma + \theta + \delta + 3\beta + 4a + f$. In the unsuccessful case, $T^{(j)}$ is the sum of RTS packet transmission period and an SIFS. Let TP_{4F} be the sum of the last unsuccessful transmission period and DIFS, then TP_{4F} is $\gamma + a + f$. In order to calculate the throughput of 4-WH CSMA/CA, we modify the analysis on previous Section 4.2 Substituting TP_S and TP_F with TP_{4S} and TP_{4F} respectively, we can easily obtain $B(TP_{4S})$ and $U(TP_{4F})$. Using (18) and (19) and calculating forms of $B(TP_{4S})(U(TP_{4S}))$ and $B(TP_{4F})(U(TP_{4F}))$, we can obtain $B(1)$ and $U(1)$.

$$\begin{aligned}\overline{B} &= B(1)\\ &= d(1) + \left\{TP_{4S} + \left[1 - (1-g)^{(TP_{4S}/a)}\right] B\left(TP_{4S}\right)\right\} u(1)\\ &\quad + \left\{TP_{4F} + \left[1 - (1-g)^{(TP_{4F}/a)}\right] B\left(TP_{4F}\right)\right\} [1 - u(1)], \end{aligned} \tag{25}$$

$$\begin{aligned}\overline{U} &= U(1)\\ &= \left\{1 + [1 - (1-g)^{(TP_{4S}/a)}]U(TP_{4S})\right\} u(1)\\ &\quad + \left\{[1 - (1-g)^{(TP_{4F}/a)}]U(TP_{4F})\right\} [1 - u(1)], \end{aligned} \tag{26}$$

where $d(1)$ and $u(1)$ is given in (20) and (21). From (24), (25) and (26), we can derive the throughput of 4-WH CSMA/CA. In the case of the infinite population model, the throughput derivations of the 4-WH CSMA/CA are given in Appendix A.3.

5. Delay Analysis

5.1. Basic CSMA/CA

In a 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). 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 the sensing channel to the accessing channel. This is one of the following three cases; (1) A packet arrives and senses the channel as idle period $(\overline{I})$. (2) A packet arrives and senses the channel as delay period $(\overline{D})$. (3) A packet arrives and senses the channel as transmission period $(\overline{B}-\overline{D})$. In the case of (1), an arbitrary packet has arrived and will find the channel idle with probability $\overline{I}/(\overline{I}+\overline{B})$. The average delay is DIFS. In the case of (2), a packet has arrived and will find the channel in the delay period with probability $\overline{D}/(\overline{I}+\overline{B})$. In this case, the average delay is also DIFS. In the last case, a packet has arrived and will find the channel in the period of another packet transmission period with probability $(\overline{B}-\overline{D})/(\overline{I}+\overline{B})$. In this case, the packet waits for the channel to be idle and DIFS, and delays by backoff algorithm. The average delay can be calculated by residual life period in renewal theory [11], [13]. Let T be the packet transmission period and T is $(1+a)$ in the Basic CSMA/CA model. We can get the average delay R as

$$\overline{R} = \frac{\overline{I}}{\overline{B}+\overline{I}} f + \frac{\overline{D}}{\overline{B}+\overline{I}} f + \frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}} \left[\frac{\overline{\left(T+f+E[D^{(2)}]\right)^2}}{2\overline{\left(T+f+E[D^{(2)}]\right)}} \right]. \tag{27}$$

In (27), we can obtain $\overline{I}$, $E[D^{(2)}]$ and $\overline{B}$ using (7), (11) and (12) repectively. We can calculate $\overline{D}$ as follows

$$\overline{D} = E[D^{(1)}] + (\overline{J}-1)E[D^{(2)}]. \tag{28}$$

We can obtain the normalized average packet delay by

$$L = \left(\frac{G}{S}-1\right)[T+\overline{Y}+\overline{R}] + T + \overline{R}, \tag{29}$$

where Y denotes random delay for a collided packet that waits for Y before sensing the channel. T means the packet transmission period and T is $(1+a)$ in the Basic CSMA/CA. The average packet delay of Basic CSMA/CA in the infinite population model is given in Appendix B.1.

5.2. Stop-and-Wait CSMA/CA

As in the case of Basic CSMA/CA, we calculate the average delay for the interval of successive transmission by

$$\begin{aligned}\overline{R} \;=\; & \frac{\overline{I}}{\overline{B}+\overline{I}} f + \frac{\overline{D}}{\overline{B}+\overline{I}} f + \frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}} \\ & \cdot \left\{ P_{Succ} \left[\frac{\overline{[TP_S+d(TP_S)]^2}}{2\overline{[TP_S+d(TP_S)]}} \right] + P_{Fail} \left[\frac{\overline{[TP_F+d(TP_F)]^2}}{2\overline{[TP_F+d(TP_F)]}} \right] \right\},\end{aligned} \tag{30}$$

where TP_S is the sum of the last successful transmission period and DIFS with $1+\beta+\gamma+2a+f$ and TP_F is the sum of the last unsuccessful transmission period and DIFS with $1+a+f$. P_{Succ} denotes the probability of a successful packet transmission which is (G/S) and P_{Fail} is $1-P_{\text{Succ}}$. Other notations are the same as those of previous Section 5.1, but $\overline{D}$ has to be calculated differently. $\overline{D}$ can be obtain by $D(1)$ as follows

$$\begin{aligned}\overline{D} &= D(1)\\ &= f+\left\{d(TP_S)+\left[1-(1-g)^{(TP_S/a)}\right]D(TP_S)\right\}u(1)\\ &\quad+\left\{d(TP_F)+\left[1-(1-g)^{(TP_F/a)}\right]D\,(TP_F)\right\}[1-u(1)],\end{aligned} \tag{31}$$

where $d(*)$ and $u(*)$ are obtained in (20) and (21). $D(TP_S)$ and $D(TP_F)$ can be calculated by substituting 1 with TP_S and TP_F respectively in (31) and calculating two equations with two unknowns $D(TP_S)$ and $D(TP_F)$.

$$D(TP_S)=\frac{\left[\begin{array}{c}[1-(1-g)^{(TP_S/a)M}][f+d(TP_S)]u(TP_F)\\ -\left\{\left[1-(1-g)^{(TP_S)M}][f+d(TP_F)\right]-d(TP_S)+d(TP_F)\right\}u(TP_S)\\ +d(TP_F)+f\end{array}\right]}{\left[\begin{array}{c}(1-g)^{(TP_S/a)M}\left\{1-\left[1-(1-g)^{(TP_S/a)M}\right]u(TP_S)\right\}\\ +\left[1-(1-g)^{(TP_F/a)M}\right](1-g)^{(TP_S/a)M}u(TP_F)\end{array}\right]}, \tag{32}$$

$$D(TP_F)=\frac{\left[\begin{array}{c}\left[d(TP_F)+f\right]\left\{[1-(1-g)^{(TP_S/a)M}]\left[u(TP_F)-u(TP_S)\right]+1\right\}\\ +[d(TP_S)-d(TP_F)]\,u(TP_F)\end{array}\right]}{\left[\begin{array}{c}(1-g)^{(TP_S/a)M}\left\{1-\left[1-(1-g)^{(TP_S/a)M}\right]u(TP_S)\right\}\\ +\left[1-(1-g)^{(TP_F/a)M}\right](1-g)^{(TP_S/a)M}u(TP_F)\end{array}\right]}. \tag{33}$$

Since the backoff delay is determined by the previous transmission period, we have to calculate the backoff delay in both the cases of successful and unsuccessful transmission period. T_S is the successful transmission period $(1+\beta+\gamma+2a)$ and T_F is the unsuccessful transmission period $(1+a)$. Then, normalized delay L in SW CSMA/CA is obtained easily by substituting former T by T_F and later T by T_S in (29).

$$L=\left(\frac{G}{S}-1\right)[T_F+\overline{Y}+\overline{R}]+T_S+\overline{R}. \tag{34}$$

In the case of the infinite population model, we can obtain the normalized delay by using a method similar to that used in calculating throughput in Appendix B.2.

5.3. 4-Way Handshake CSMA/CA

In 4-WH CSMA/CA, the packet transmission period is different to that of SW CSMA/CA. Since we have assumed that TP_{4S} is $1+\gamma+\theta+\delta+3\beta+4a+f$, TP_{4F} is $\gamma+a+f$, T_{4S} is $1+\gamma+\theta+\delta+3\beta+4a$ and T_{4F} is $\gamma+a$, we calculate the average delay for the interval of successive transmission $(\overline{R})$ by

$$\begin{aligned}\overline{R} &= \frac{\overline{I}}{\overline{B}+\overline{I}}f+\frac{\overline{D}}{\overline{B}+\overline{I}}f+\frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}}\\ &\quad\cdot\left\{P_{\text{Succ}}\left[\frac{\overline{[TP_{4S}+d(TP_{4S})]^2}}{2\overline{[TP_{4S}+d(TP_{4S})]}}\right]+P_{\text{Fail}}\left[\frac{\overline{[TP_{4F}+d(TP_{4F})]^2}}{2\overline{[TP_{4F}+d(TP_{4F})]}}\right]\right\}\end{aligned} \tag{35}$$

where P_{Succ} denotes the probability that a packet transmission is successful which is (G/S) and P_{Fail} is $1 - P_{\text{Succ}}$ as the same in the Section 5.2 $\overline{D}$ has to be calculated in a manner similar to that of SW CSMA/CA. $\overline{D}$ is a recursive form as in (31) by substituting TP_S with TP_{4S} and TP_F with TP_{4F}. Then, the normalized delay L in 4-WH CSMA/CA is easily obtained by substituting former T_F with T_{4F} and later T_S with T_{4S} in (34). In the infinite population model, we can easily obtain the packet delay similar to the case of SW CSMA/CA. The derivations of packet delay for infinite population are given in Appendix B.3.

6. 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. For simulation model, we have assumed that channel has no error except the case of packet collision and the propagation delay is identical for all terminals. We used the SIMSCRIPT II.5 which is the event-driven and process oriented simulation language. We have considered the performance with the variation of M (the number of users), G (offered load), p (transmission probability) and γ (RTS transmission period). We have considered values of each parameter based on real communication environments and the IEEE 802.11 standard draft as well [9], [14],[15].

Figures 4 and 5 show the throughput and the packet delay curves versus offered traffic load for the Basic CSMA/CA system with varying the numbers of users. A line represents analytical results and a symbol does a simulation check points. The simulation check points include the error levels of 5%. Simulation results are very close to those of analysis under the condition of low loading, while some difference is shown at moderate to high loading. This is why g is assumed to new arrivals as well as retransmission. This is a common approximation for the case of an infinite user population under certain restrictions regarding the retransmission scheme. For a finite population. it is reasonable to expect this approximation to work well at low load, while it is not always at high loading. In Figure 4, the throughput is not very sensitive to the number of users when the traffic is low, while it is degraded when the traffic load is increased above 10. The normalized packet delay also increased exponentially when the traffic load is above 10.

Figures 6 and 7 show the analytical results of the SW CSMA/CA for varying the transmission probability p. The choice of p value should be seriously considered in a wireless CSMA/CA system, since it is related to the average contention window size and the performance of the system. This p value is decreased exponentially according to the number of retransmission [9], we assumed the p value is constant in this paper. This problem is also considered in [8]. In these graphes, we have found that the performance is maximized when p is from 0.03 to 0.04 for the traffic load in the range from 0.1 to 4.

The analytical results of the throughput and the packet delay for 4-WH CSMA/CA are shown in Figures 8 and 9 with varying the length of RTS packet transmission period (γ). The throughput characteristics is sustained above specific offered load and decreased linearly as the increase of RTS packet transmission time. The packet delay is raised exponentially as the incease of the γ. As shown from Figure 8 to Figure 9, we have found that the RTS packet size is the degrading factor for the performance of CSMA/CA protocol.

In order to compare three types of CSMA/CA, the throughput and the packet delay comparisons for three type CSMA/CA versus offered traffic load G are plotted in Figures 10

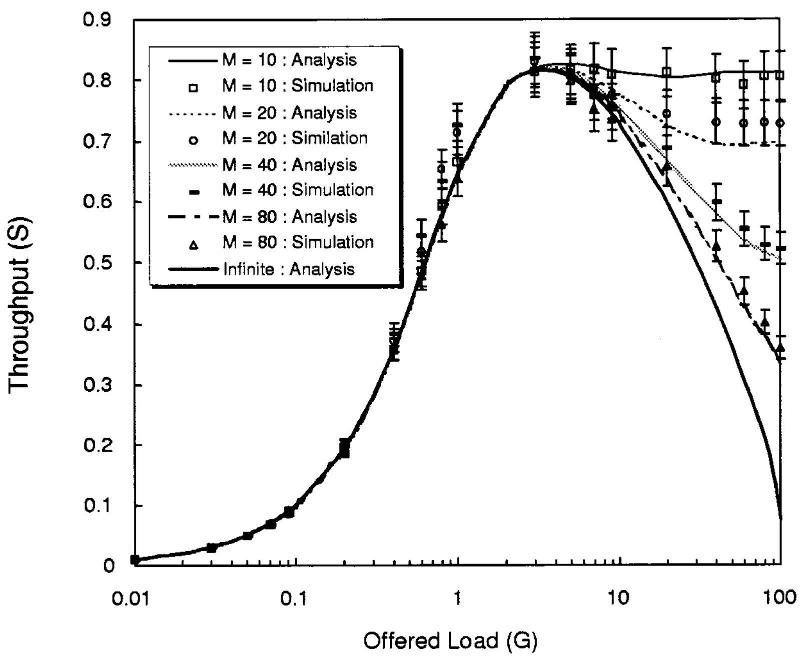

Figure 4. Throughput of Basic CSMA/CA protocols for varying the number of users ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\overline{Y} = 0.06$).

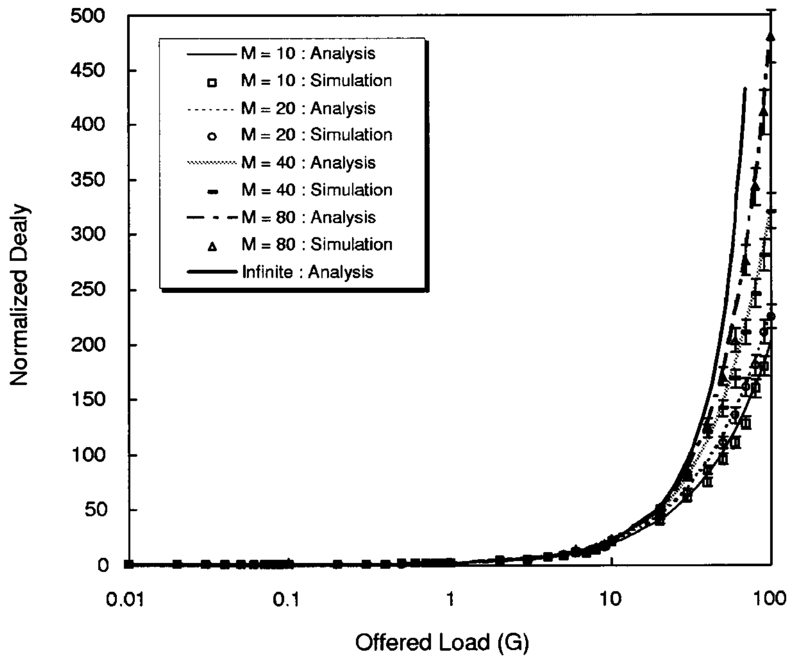

Figure 5. Packet delay of Basic CSMA/CA protocols for varying the number of users ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\overline{Y} = 0.06$).

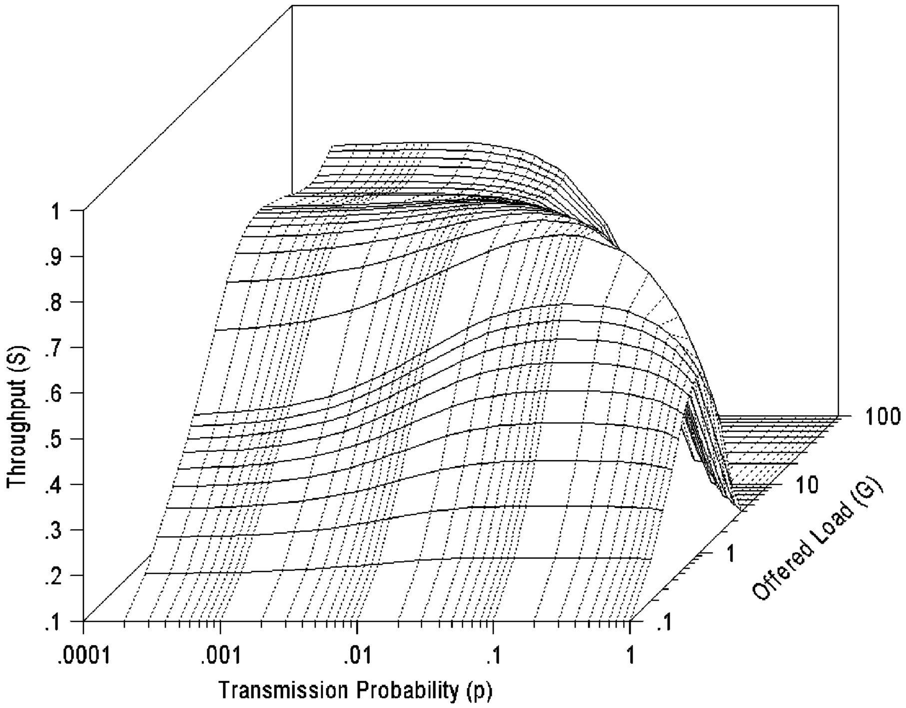

Figure 6. Throughput of Stop-and-Wait CSMA/CA protocols for varying p. ($a = 0.01$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$, $M = 30$, $\overline{Y} = 0.06$).

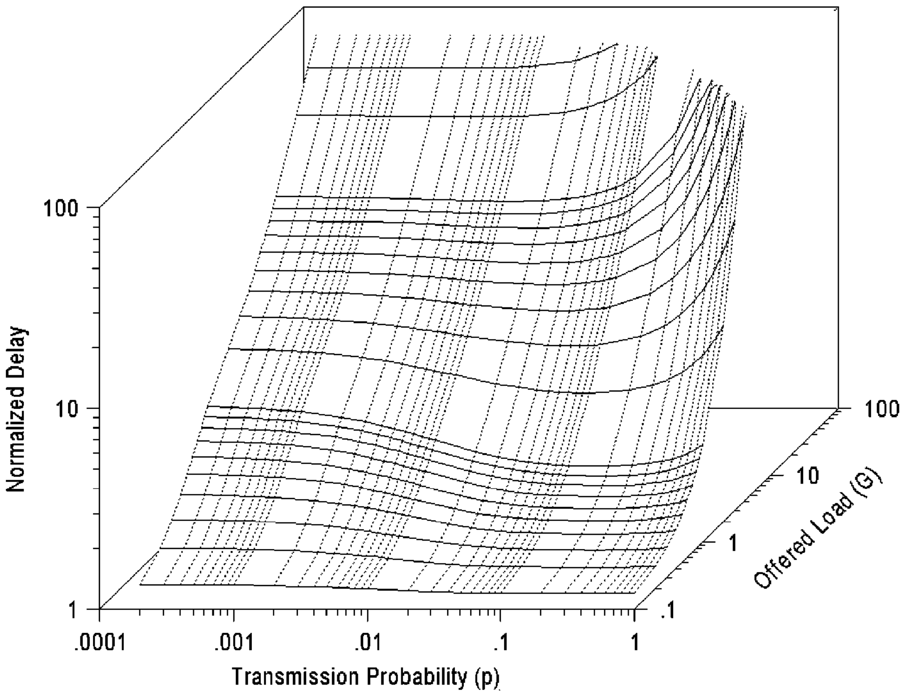

Figure 7. Packet delay of Stop-and-Wait CSMA/CA protocols for varying p. ($a = 0.01$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$, $M = 30$, $\overline{Y} = 0.06$).

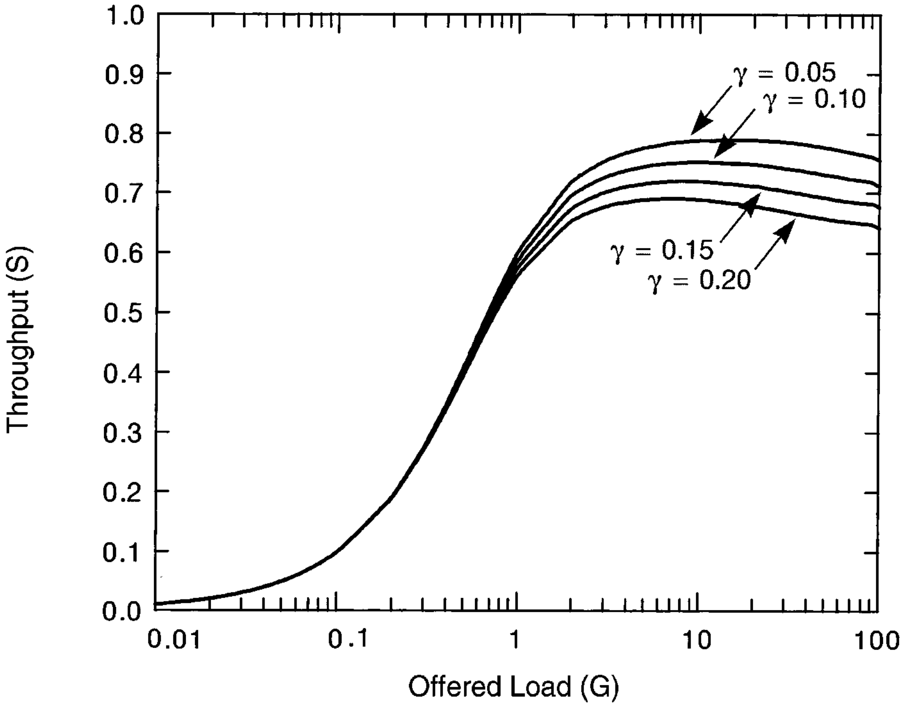

Figure 8. Throughput of 4-Way Handshake CSMA/CA protocols for varying the transmission time of RTS packet ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$, $\theta = 0.03$, $M = 20$, $\overline{Y} = 0.06$).

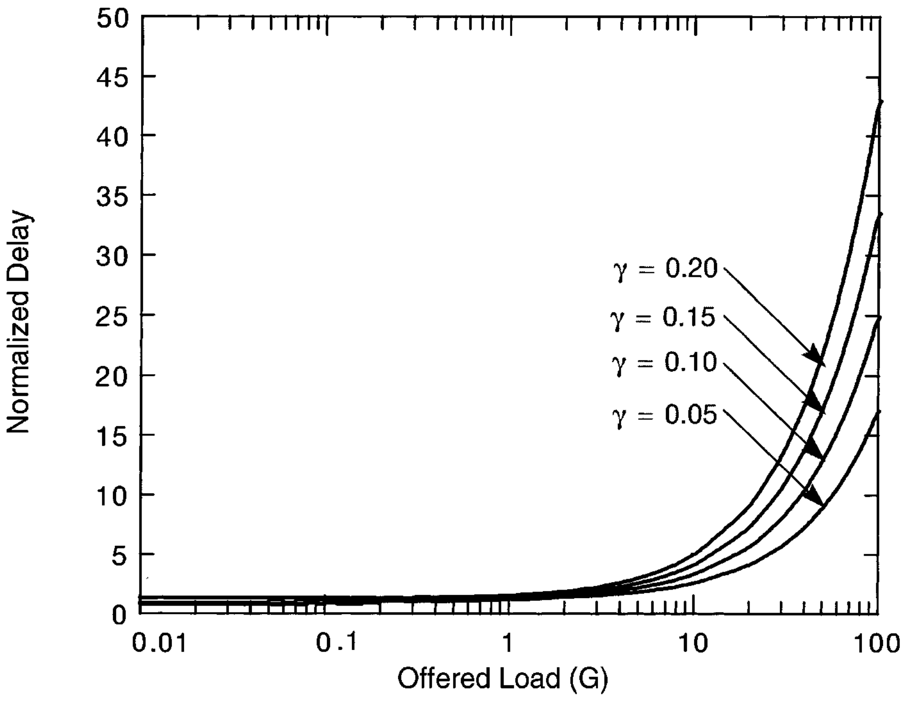

Figure 9. Packet delay of 4-Way Handshake CSMA/CA protocols for varying the transmission time of RTS packet ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\beta = 0.01$, $\delta = 0.03$, $\theta = 0.03$, $M = 20$, $\overline{Y} = 0.06$).

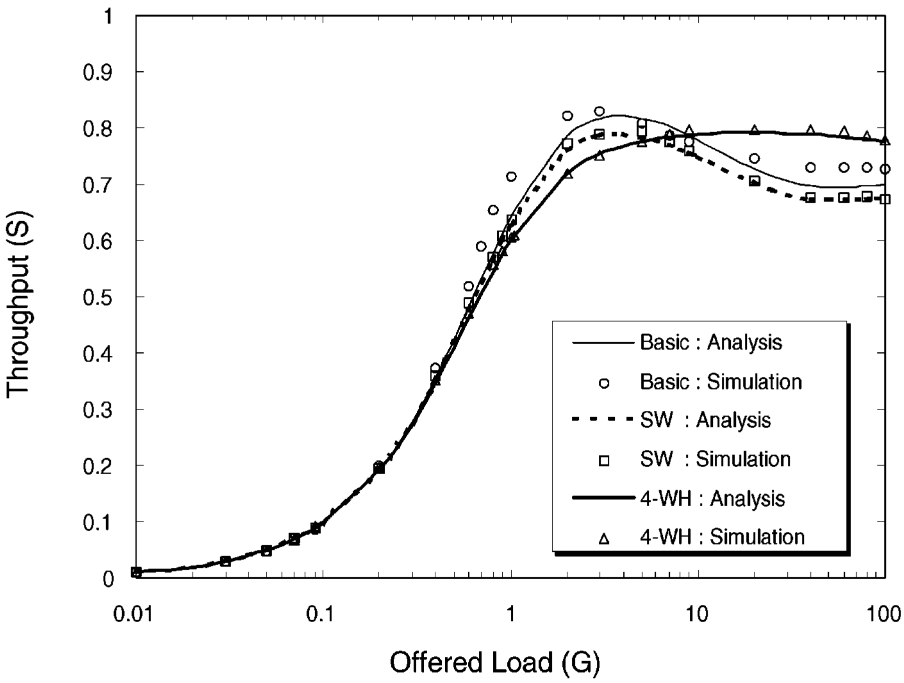

Figure 10. Throughput comparison of three types of CSMA/CA protocols in the finite population model ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\gamma = 0.05$, $\beta = 0.01$, $\delta = 0.03$, $\theta = 0.03$, $M = 20$, $\overline{Y} = 0.06$).

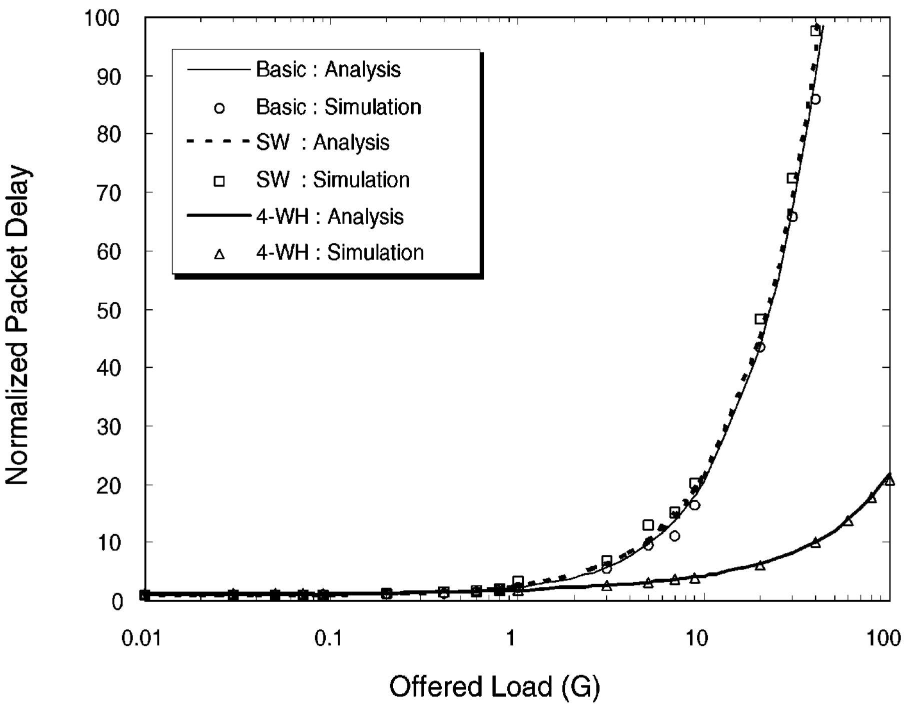

Figure 11. Packet delay comparison of three types of CSMA/CA protocols in the finite population model ($a = 0.01$, $p = 0.03$, $f = 0.03$, $\gamma = 0.05$, $\beta = 0.01$, $\delta = 0.03$, $\theta = 0.03$, $M = 20$, $\overline{Y} = 0.06$).

and 11. In Figures 10 and 11, a line represents analytical results and a symbol represents a simulation check point. The throughput of Basic CSMA/CA is superior to other two types in low traffic, but that of 4-WH CSMA/CA shows the highest value in high traffic load. The delay characteristics are shown in Figure 11. The delay of Basic CSMA/CA is the lowest in comparison to that of the other two types of CSMA/CA in low traffic load, while the 4-WH CSMA/CA shows the lowest delay in high traffic load.

7. Conclusions

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, has been analyzed and presented. In order to analyze the performance of CSMA/CA protocol in practical wireless LAN environments, we have considered that network is composed of finite number of users at first 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 concurs with previous research. Based on the analysis, the performance of the slotted CSMA/CA is affected by traffic loads, SIFS, DIFS, ACK, RTS, and CTS packet length as intuitively expected. We have found that the transmission probability p is very important factor to optimize the performance of the wireless LAN system and also found that 4-WH CSMA/CA protocol is more appropriate than others in high traffic loads. The main contributions of this paper are threefold: (1) the development of an analytical approach for evaluating the performance of CSMA/CA protocols in wireless LANs, (2) the performance comparison of three types of CSMA/CA protocols, and (3) we have checked our analytical results with those of computer simulations. The analysis techniques and results of this paper will be helpful in practical applications and designs in wireless LANs.

Appendix A. Throughput for the Infinite Population Model

The throughput derivations of CSMA/CA in the infinite population model are based on

$$S = \frac{\overline{U}}{\overline{B} + \frac{a}{[1-e^{-aG}]}}. \tag{36}$$

A.1. Basic CSMA/CA

In the case of Basic CSMA/CA protocol, we can modify (12) and (14) for the infinite population model as

$$\begin{aligned}\overline{B} &= E[B^{(1)}] + (\overline{J} - 1)E[B^{(2)}] \\ &= f[1 - e^{-aG}] + 1 + a + \left(\frac{1}{e^{-TPG}} - 1\right) \\ &\quad \cdot \left[f + \frac{ae^{-aG(1+TP)}}{1 - e^{-aGTP}} \sum_{n=1}^{\infty} \left(\frac{[(1-p)aGTP]^n}{[1-(1-p)^n e^{-aG}]n!}\right) + 1 + a\right],\end{aligned} \tag{37}$$

$$
\begin{aligned}
\overline{U} &= E[U^{(1)}] + (\overline{J} - 1)E[U^{(2)}] \\
&= \frac{aGe^{-aG}}{1 - e^{-aG}} + \left(\frac{1}{e^{-TPG}} - 1\right) \\
&\quad \cdot \sum_{n=1}^{\infty} \left\{ \frac{[np + (1-p)aG][e^{-aG}(1-p)^n]^2}{(1-p)[1 - e^{-aG}(1-p)^n]} + np(1-p)^{n-1} \right\} \left\{ \frac{e^{-GTP}[GTP]^n}{[1 - e^{-GTP}]n!} \right\}.
\end{aligned}
\tag{38}
$$

Using (36), (37) and (38), we can calculate the throughput of basic CSMA/CA in the infinite population model.

A.2. Stop-and-Wait CSMA/CA

The throughput of SW CSMA/CA protocols can be derived from (24). The $B(1)$ and $U(1)$ for SW CSMA/CA are as follow

$$
\begin{aligned}
\overline{B} &= B(1) \\
&= d(1) + \left\{TP_S + \left[1 - e^{-aGTP_S}\right] B\,(TP_S)\right\} u(1) \\
&\quad + \left\{TP_F + \left[1 - e^{-aGTP_F}\right] B\,(TP_F)\right\} [1 - u(1)],
\end{aligned}
\tag{39}
$$

$$
\begin{aligned}
\overline{U} &= U(1) \\
&= \left\{1 + [1 - e^{-GTP_S}]U(TP_S)\right\} u(1) \\
&\quad + \left\{[1 - (1 - e^{-GTP_F}]U(TP_F)\right\} [1 - u(1)],
\end{aligned}
\tag{40}
$$

where

$$
\begin{aligned}
B(TP_S) &= \frac{\left[\begin{array}{c} [1 - e^{-GTP_F}][TP_s + f + d(TP_s)]u(TP_F) \\ -\left\{[1 - e^{-GTP_F}][TP_s + f + d(TP_F)] - \alpha - \beta - \gamma\right\} u(TP_S) \\ +[1 - e^{-GTP_F}][d(TP_F) - d(TP_s)] + d(TP_S) + f + 1 + a \end{array}\right]}{\left[\begin{array}{c} e^{-GTP_F}\left\{1 - [1 - e^{-GTP_S}]u(TP_S)\right\} \\ +e^{-GTP_S}\left\{[1 - e^{-GTP_F}]u(TP_F)\right\} \end{array}\right]}, \\
B(TP_F) &= \frac{\left[\begin{array}{c} (1 + a + f)\left\{[1 - e^{GTP_S}][u(TP_F) - u(TP_S)] + 1\right\} \\ -[1 - e^{-GTP_S}][u(TP_S)d(TP_F) - u(TP_F)d(TP_S)] \\ +d(TP_F) + u(TP_F)(a + \beta + \gamma) \end{array}\right]}{\left[\begin{array}{c} e^{-GTP_F}\left\{1 - [1 - e^{-GTP_S}]u(TP_S)\right\} \\ +e^{-GTP_S}\left\{[1 - e^{-GTP_F}]u(TP_F)\right\} \end{array}\right]},
\end{aligned}
\tag{41}
$$

and

$$
\begin{aligned}
U(TP_S) &= \frac{u(TP_S) - [1 - e^{-GTP_F}][u(TP_S) - u(TP_F)]}{\left[\begin{array}{c} e^{-GTP_F}\left\{1 - [1 - e^{-GTP_S}]u(TP_S)\right\} \\ +e^{-GTP_S}\left\{[1 - e^{-GTP_F}]u(TP_F)\right\} \end{array}\right]}, \\
U(TP_F) &= \frac{u(TP_F)}{\left[\begin{array}{c} e^{-GTP_F}\left\{1 - [1 - e^{-GTP_S}]u(TP_S)\right\} \\ +e^{-GTP_S}\left\{[1 - e^{-GTP_F}]u(TP_F)\right\} \end{array}\right]},
\end{aligned}
\tag{42}
$$

where $d(*)$ and $u(*)$ terms are derived from (20) and (21) as

$$\begin{aligned} d(1) &= f[1-e^{-aG}], \\ d(TP_S) &= \frac{ae^{-aG(1+TP_S)}}{1-e^{-aGTP_S}}\sum_{n=1}^{\infty}\left(\frac{[(1-p)aGTP_S]^n}{[1-(1-p)^n e^{-aG}]n!}\right), \\ d(TP_F) &= \frac{ae^{-aG(1+TP_F)}}{1-e^{-aGTP_F}}\sum_{n=1}^{\infty}\left(\frac{[(1-p)aGTP_F]^n}{[1-(1-p)^n e^{-aG}]n!}\right), \end{aligned} \tag{43}$$

$$\begin{aligned} u(1) &= \frac{aGe^{-aG}}{1-e^{-aG}}, \\ u(TP_S) &= \sum_{n=1}^{\infty}\left\{\frac{[np+(1-p)aG][e^{-aG}(1-p)^n]^2}{(1-p)[1-e^{-aG}(1-p)^n]}+np(1-p)^{n-1}\right\}\left\{\frac{e^{-GTP_S}(GTP_S)^n}{(1-e^{-GTP_S})n!}\right\}, \\ u(TP_F) &= \sum_{n=1}^{\infty}\left\{\frac{[np+(1-p)aG][e^{-aG}(1-p)^n]^2}{(1-p)[1-e^{-aG}(1-p)^n]}+np(1-p)^{n-1}\right\}\left\{\frac{e^{-GTP_F}(GTP_F)^n}{(1-e^{-GTP_F})n!}\right\}. \end{aligned} \tag{44}$$

In the infinite population model, we can get the throughput of SW CSMA/CA using (36), (39) and (40).

A.3. 4-Way Handshake CSMA/CA

In the case of 4-WH CSMA/CA protocol, the throughput can be derived as the same manner in the case of SW CSMA/CA. We modify (39) and (40) as

$$\begin{aligned} \overline{B} &= B(1) \\ &= d(1)+\left\{TP_{4S}+\left[1-e^{-GTP_{4S}}\right]B\left(TP_{4S}\right)\right\}u(1) \\ &\quad +\left\{TP_{4F}+\left[1-e^{-GTP_{4F}}\right]B\left(TP_{4F}\right)\right\}[1-u(1)], \end{aligned} \tag{45}$$

$$\begin{aligned} \overline{U} &= U(1) \\ &= \left\{1+[1-e^{-GTP_{4S}}]U(TP_{4S})\right\}u(1) \\ &\quad +\left\{[1-e^{-GTP_{4F}}]U(TP_{4F})\right\}[1-u(1)], \end{aligned} \tag{46}$$

where $B\left(TP_{4S}\right)$, $B\left(TP_{4F}\right)$, $U\left(TP_{4S}\right)$ and $U\left(TP_{4F}\right)$ are derived from (41) and (42), substituting TP_S and TP_F with TP_{4S} and TP_{4F} respectively. In (45) and (46), $d(1)$ and $u(1)$ are given in (43) and (44). The throughput of 4-HW CSMA/CA in the infinite population model using (36), (45) and (46).

Appendix B. The Packet Delay for the Infinite Population Model

B.1. BASIC CSMA/CA

In order to calculate the packet delay for Basic CSMA/CA in the infinite population model, we use the derivations in the finite population model. We use (27) and (29) in Section 5.1 However, $D^{(2)}$ and $\overline{D}$ should be caculated as

$$D^{(2)} = \frac{ae^{-aG(1+TP)}}{1-e^{-aGTP}} \sum_{n=1}^{\infty} \left(\frac{[(1-p)aGTP]^n}{[1-(1-p)^n e^{-aG}]n!} \right), \tag{47}$$

$$\begin{aligned} \overline{D} &= E[D^{(1)}] + (\overline{J}-1)E[D^{(2)}], \\ &= f[1-e^{-aG}] + \left(\frac{1}{e^{-TPG}} - 1 \right) \left[\frac{ae^{-aG(1+TP)}}{1-e^{-aGTP}} \sum_{n=1}^{\infty} \left(\frac{[(1-p)aGTP]^n}{[1-(1-p)^n e^{-aG}]n!} \right) \right]. \end{aligned} \tag{48}$$

We can calculate the normalized packet delay for Basic CSMA/CA in the infinite population model using (47), (48), (27) and (29).

B.2. STOP-AND-WAIT CSMA/CA

In the case of SW CSMA/CA, we use the results of (30) in Section 5.2 In (30), $\overline{D}$ should be derived on the basis of Poisson distribution as follows

$$\begin{aligned} \overline{D} &= D(1) \\ &= f + \left\{ d(TP_S) + \left[1-e^{GTP_S}\right] D(TP_S) \right\} u(1) \\ &\quad + \left\{ d(TP_F) + \left[1-e^{GTP_F}\right] D\,(TP_F) \right\} [1-u(1)], \end{aligned} \tag{49}$$

where $d(*)$ and $u(*)$ are obtained in (43) and (44). $D(TP_S)$ and $D(TP_F)$ can be calculated by substituting 1 with TP_S and TP_F respectively in (49) and calculating two equations with two unknowns $D(TP_S)$ and $D(TP_F)$.

$$D(TP_S) = \frac{\left[\begin{array}{c} [1-e^{-GTP_S}][f+d(TP_S)]u(TP_F) \\ -\left\{ \left[1-e^{-GTP_S}][f+d(TP_F)\right] - d(TP_S) + d(TP_F) \right\} u(TP_S) \\ +d(TP_F) + f \end{array} \right]}{\left[\begin{array}{c} e^{-GTP_S} \left\{ 1 - \left[1-e^{-GTP_S}\right] u(TP_S) \right\} \\ + \left[1-e^{-GTP_F}\right] e^{-GTP_S} u(TP_F) \end{array} \right]}, \tag{50}$$

$$D(TP_F) = \frac{\left[\begin{array}{c} \left[d(TP_F) + f\right] \left\{ [1-e^{-GTP_S}]\,[u(TP_F) - u(TP_S)] + 1 \right\} \\ + [d(TP_S) - d(TP_F)]\,u(TP_F) \end{array} \right]}{\left[\begin{array}{c} e^{-GTP_S} \left\{ 1 - \left[1-e^{-GTP_S}\right] u(TP_S) \right\} \\ + \left[1-e^{-GTP_F}\right] e^{-GTP_S} u(TP_F) \end{array} \right]}. \tag{51}$$

Using (30), (34), (43), (44) and (49), The normalized packet delay in the infinite population model can be derived.

B.3. 4-WAY HANDSHAKE CSMA/CA

Normalized delay of 4-WH CSMA/CA in the infinite population model can be calculated as the same manner in the case of that of finite source model. We consider (35) and derive the $\overline{D}$ as

$$\begin{aligned}\overline{D} &= D(1)\\ &= f + \left\{d(TP_{4S}) + \left[1 - e^{-GTP_{4S}}\right] D(TP_{4S})\right\} u(1)\\ &\quad + \left\{d(TP_{4F}) + \left[1 - e^{-GTP_{4F}}\right] D\,(TP_{4F})\right\} [1 - u(1)],\end{aligned} \tag{52}$$

where $d(*)$ and $u(*)$ are obtained in (43) and (44). $D(TP_{4S})$ and $D(TP_{4F})$ can be derived by substituting TP_S and TP_F with TP_{4S} and TP_{4F} respectively in (50) and (51). From (35) and (52), we get the average packet delay of 4-WH CSMA/CA in the infinite population using $D(TP_{4S})$ and $D(TP_{4F})$ as

$$L = \left(\frac{G}{S} - 1\right) [T_{4F} + \overline{Y} + \overline{R}] + T_{4S} + \overline{R}. \tag{53}$$

References

1. K. Pahlavan and A.H. Levesque, “Wireless Data Communications”, Proc. o the IEEE , Vol. 82, No. 9, pp. 1398–1430, 1994.
2. T. Wilkinson, T.G.C. Phipps and S.K. Barton, “A Report on HIPERLAN Standardization”, International Journal of Wireless Information Networks, Vol. 2, No. 2, pp. 99–120, 1995.
3. N. Abramson, “Multiple Access in Wireless Digital Networks”, Proc. of the IEEE , Vol. 82, No. 9, pp. 1360–1370, 1994.
4. K.C. Huang and K.C. Chen, “Interference Analysis of Nonpersistent CSMA with Hidden Terminals in Multicell Wireless Data Networks,” Proc. IEEE PIMRC ’95, Toronto, Canada, 1995, pp. 907–911.
5. 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, Toronto, Canada, 1995, pp. 613–617.
6. M. Nor and J. Semarak, “Performance of CSMA-CA MAC Protocol for Distributed Radio Local Area Networks”, Proc. IEEE PIMRC ’95, Toronto, Canada, 1995, pp. 912–916.
7. A. Visser and M.E. Zarki, “Voice and Data Transmission over an 802.11 Wireless Network,” Proc. IEEE PIMRC ’95, Toronto, Canada, 1995, pp. 648–652.
8. Weinmiller, H. Woesner, J.P. Ebert and A. Wolisz, “Analyzing the RTS/CTS 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/
9. Wireless LAN Medium Access Control (MAC) And Physical Layer (PHY) Specification, IEEE Standard Draft, 1994.
10. H. Takagi and L. Kleinrock, “Throughput Analysis for CSMA Systems”, IEEE Trans. Commun., Vol. COM 33, No. 7, pp. 627–638, 1985.
11. 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. Commun., Vol. com-23, No. 12, pp. 1400–1416, 1975.
12. F.A. Tobagi and V.B. Hunt, “Performance Analysis of Carrier Sense Multiple Access with Collision Detection”, Computer Networks, Vol. 4, pp. 245–259, 1980.
13. L. Kleinrock, Queueing System Vol. 1: Theory, Wiley, 1975, pp. 169.
14. G. Ennis, P. Belanger and W. Diepstraten, “DFWMAC (Distributed Foundation Wireless Medium Access Control) Proposal”, IEEE P802.11-93/190.
15. D. Bagby, Bob O’Hara and Dave Roberts, “A Compromise Proposal for Revisions to the MAC Frame Formats to Support Wireless Distribution Systems”, IEEE P802.11-94/290.

(Photograph not available at time of printing)

Jae Hyun Kim was born in Seoul, South Korea. He received the B.Sc., the M.Sc. and the Ph.D. degrees, all in computer science and engineering, from Hanyang University, Ansan, Korea, in 1991, 1993, and 1996, respectively. He received LG Communication Prize Award for communication papers supported LG communication Co. in 1993, and received Samsung Humantech Thesis Prize Award for Wireless Communication paper in 1997. He received the summa cum laude in 1991 from Department of Computer Science and Engineering, Hanyang University, Ansan, Korea. He spent two months as a visiting scholar in the Communication Research Laboratory (CRL), Tokyo, Japan in 1996. From April 1997 to October 1998 he worked as a post-doctoral fellow in the Department of Electrical Engineering, University of California Los Angeles, CA, U.S.A. Since November 1998 he has been with the Next Generation Network System Engineering Department at Bell Laboratories, Lucent Technologies at Holmdel, NJ, U.S.A. His research interests include Multiple Access Control (MAC) and data link control protocols for high speed wireless communication and performance modeling and analysis of hybrid networks support wireless and wireline services.

Dr. Kim is a member of the Korean Institute of Communication Sciences (KICS), the Korea Institute of Telematics and Electronics (KITE), The Korea Information Science Society (KISS) and IEEE.

(Photograph not available at time of printing)

Jong Kyu Lee was born in Seoul, South Korea. He received the B.E. degree in electrical engineering from Hanyang University, Seoul, Korea. in 1979, and the M.S. and the Ph.D. degrees, all in electrical engineering, from UCLA, Los Angeles, CA, U.S.A. in 1987 and 1989, respectively. He has been with the Department of Computer Science and Engineering at Hanyang University since 1989, where he is now a Associate Professor. His research interests include wireless Local Area Networks, mobile communication, satellite communication, and performance analysis of communication systems. Between 1979 and 1984, he worked for Advanced Development of Defense (ADD) as technical staff. In March 1989 he joined the communication research laboratory in Samsung Electronics Co. as a chief of technical staff. He has worked on integrated data/voice wireless local area networks, circuit-switched grid topology networks, wireless transmission techniques, optical communications. He also worked on multiple access protocols, data flow control problem in packet switched networks. He has published over 50 papers and 2 books with coauthors.

Dr. Lee is a Technical Editor for the Korean Institute of Communication Sciences (KICS), the Korea Institute of Telematics and Electronics(KITE), and The Korea Information Science Society (KISS). He is also a member of IEEE and IEICE (Japan).